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High-resolution modelling of interactions between soil moisture and convective development in a mountain enclosed Tibetan basin

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Response to reviewers and changes to manuscript

We would like to thank once again both reviewers and the editor for their work. The reviewer's comments are much appreciated and have improved the clarity and legibility of the manuscript. Below is our response to all reviewer comments and changes made to the revised manuscript. Our response is always printed in **red**. Text modifications are put in quotation marks. All

⁵ Our response is always printed in **red**. Text modifications are put in quotation marks. All changes (except spelling mistakes) were also highlighted in in the uploaded pdf-document of the revised article as well as the revised manuscript (LATEX-source). Line numbers of the revised manuscript are indicated and the text modifications are highlighted in **red** the updated version of the manuscript found below.

10 Reviewer 1

- 1. In their simulations, the authors set the initial soil moisture to 2.0 the field capacity, which corresponds in their case to realistic conditions. I wonder why the authors did not increase the soil moisture further to more humid conditions? During the 2012 field campaign we observed soil moistures that corresponded to values ranging from close to the permanent wilting point to circa $2 \times$ field capacity. It should be noted that the field campaign was conducted during the summer monsoon season so that soil moistures were typically higher than during the non-monsoon season. Soil moistures exceeding $2 \times FC$ were not observed, so that it was decided to not include these into the design of the simulations. The limited availability of fair weather days with radiosonde launches for the initialization of the simulations led to the choosing of this particular day, during which the soil moisture was to $2 \times FC$.
- 2. The only thing I was really missing in this paper is an analysis of convection indices, like CAPE and CIN. Especially, the response of CIN to soil moisture varia- tions is decisive for convection initiation. Perhaps the authors could include some text or even a Figure describing the response of these parameters to different initial soil moisture. We have performed an analysis of CAPE and have added a new Figure 10. The text in Sec-

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tion 3.4 (p27, L19ff) is amended by: "An analysis of convective available potential energy (CAPE) tells a similar story (Fig. 10). After sunrise, simulated CAPE-values in the Nam Co start to diverge between cases due to differences in the surface energy balance. Cases PWP and $0.75 \times {\rm FC}$ develop the least amount of CAPE, which is fully released between 9:00 LT and 14:00 LT. The moistest cases in contrast develop the largest amounts of CAPE, but it is not fully released as high soil moistures and associated lack of sensible heat fluxes reduce convection development. Consequently, CAPE is exported from the basin. Cases $0.75 \times {\rm FC}$ and $1.0 \times {\rm FC}$ present an intermediate, for which there is ample development of CAPE, which is almost fully depleted by convection during the afternoon, so that they have the highest overall release of CAPE."

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- 3. P4646, L19-21: "Through changes in the Bowen-ratio, there is a strong modifi- cation of the surface energy budget due to soil moisture." As the Bowen ratio is derived from the sensible and latent heat flux, I would formulate it the other way around: Soil moisture strongly modifies the partitioning of the availabe energy into sensible and latent heat, evident in the Bowen-ratio. We appreciate the reviewer's comment and changed the text accordingly (p25, L10: "Soil moisture strongly modifies the partitioning of the available energy into sensible and latent heat, evident in the Bowen-ratio. We appreciate the reviewer's comment and changed the text accordingly (p25, L10: "Soil moisture strongly modifies the partitioning of the available energy into sensible and latent heat, evident in the Bowen-ratio, and thus the surface energy balance."
- 4. P4648, L10: "As deep convection is primarily driven by the release of latent en- ergy..." In my opinion, this is not true. Convection is driven by boundary-layer processes or synoptic processes. The release of latent heat during condensa- tion of water vapour gives additional buoyancy, but it is not the main driver. We agree with the reviewer that the original formulation is too short and thus inaccurate. What we meant to express was that the main source of the energy released stems from latent heat release. However convection and its triggering is a process driven by processes mentioned by the reviewer. We replace the sentence with (p27, L1): "As the development of deep convection is sustained by the release of latent energy, ..."

- 5. P4648, L17: "The equivalent potential temperature profile (θ_e) reveals a predis- position for convection" In order to assess this, the profile of equivalent potential temperature assuming saturation should be plotted as well (\rightarrow conditional instability). Figure 2 was updated
- 6. P4651, top: The authors state that the upper level wind speeds used in this work are 5 unrealistically low. The role of the background wind on the soil moisture precipitation feedback was recently investigated by Froidevaux et al. (2014): In- fluence of the background wind on the local soil moisture-precipitation feedback (10.1175/JAS-D-13-0180.1). Some text relating these findings could be inserted here. We appreciate the suggested article, which was unknown to us and we included this aspect to the dis-10 cussion. Froidevaux et al. (2014) discuss the importance of circulation for convection development as moist air is transported to warm patches where convective initiation occurs. It should be pointed out that our simulation includes background winds as well as a lake-breeze (see. i.e Gerken et al., 2014) which performs this 'function'. We added the following sentence (p30, L2-): "Recent work by Froidevaux et al. (2014) 15 investigated the importance of background wind speeds and horizontal transport of convective cells during their development. While wind speeds used in this work were lower than observed, the lake-land circulation (i.e. Gerken et al, 2014) provides the necessary horizontal propagation mechanism that allows for the development of convective cells." 20
 - 7. Figure 5: One could insert another panel (h) showing the Bowen-ratios **During the draft** stage, it was experimented with a figure showing Bowen-rations. However, due to the number of lines the legibility of the figure was low, so that we did not include this in the submitted manuscript.
- 8. P4650, L17: When using 2D simulations, strictly speaking, there is no such thing as a control volume. I would prefer control domain or area. "Control volume" was replaced with "control domain" throughout the text.

- 9. Fig. 3: The red contour lines for the clouds makes this figure hard to read. Per- haps only one red contour line for the cloud boundary would be sufficient? Figure 3 was updated
- 10. Fig. 8: The legend for the grey shades is missing and the number of thin black isolines it too high, they mask the grey shades. Furthermore, the upper panel showing precipitation (?) is not explained. Figure 8 was updated
- 11. Additional minor technical or textual comments. All other comments are taken into account in the revised manuscript

Reviewer 2

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Major comments

1. A key aspect that is not discussed in much detail is the role of flux heterogeneity on the 10 development of convection. Much of the paper takes a 1D approach, looking at mean turbulent fluxes and the evolution of convection throughout the domain, but the highly heterogeneous terrain will surely induce mesoscale circulations which will have a significant impact on convective initiation. For example, the authors argue that the reduction in convection for the highest soil moisture values are due solely to a reduction in radia-15 tion due to increased cloud cover. From the results it is clear that this is indeed a factor. However, the reduction in sensible heat fluxes over land due to the high soil moisture will also reduce the land-lake temperature gradient, potentially reducing the magnitude of any mesoscale flows, and therefore convergence over land, which will also reduce the intensity of convection. I think the impact of surface heterogeneity in your results needs to 20 be discussed throughout the paper (e.g. in P4649, L1-9). For example, the authors could show 2D plots of surface fluxes/temperatures, and some quantification of convergence in the different simulations. One of the primary reasons, why flux heterogeneity was not discussed in detail in this work was the 2D-simulation approach. We believe that a 3D-approach, which was too computationally expensive for the resolutions used in 25 this work would be more suited to analyze and discuss spatial organization. Additionally, soil moisture driven mesoscale circulations are typically much less strong than lake-breezes or upslope winds. Additionally, they require comparatively large areas to develop. Previous work by Gerken et al, 2014 (10.1007/s00704-013-0987-9) investigated the influence of mesoscale circulations from both the complex terrain and the lake breeze on the development of convection, which we believe to be much more important than land induced circulations. One measure of spatial heterogeneity included in the present work is interquartile range of surface energy fluxes and solar irradiance, which is presented in Figure 5. We agree with the reviewer that there is little discussion about this aspect and propose to add the following to section 3.2 (p22, L16-)(see response to P4636 L20 for additional text):

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"The spatial variability of surface energy fluxes and solar radiation also demonstrates that surface atmosphere interactions change with increasing soil moisture. With the onset of cloud development, solar irradiance of shaded grid cells begins to drop, while the median irradiance and turbulent surface fluxes remain unaffected. With increasing cloud optical depth median shortwave radiation fluxes begin to decrease. This occurs first in the most shaded cells and then progresses to the mean fluxes. For the moister simulations $(1-2 \times FC)$ there is little difference between lower and upper quartile latent heat fluxes in the early afternoon, indicating widespread cloud cover as the main driver for the decrease. However, in the later afternoon, there is again increased variability in the simulated turbulent fluxes (both median and upper quartile) that is not accompanied with a corresponding increase in the median solar irradiation flux. This indicates that in addition to solar irradiance, local circulation systems likely play a role in the surface energy balance. The impact of local circulations on the surface energy balance, turbulent fluxes and convective triggering was investigated in Gerken et al. (2014). "

2. My other main issue (although with an easy solution) is the description of the model domain, as it is not shown in Figure 1 and there are no lat/lon coordinates of the end points. Locations such as the Nyenchen Thangla mountain chain may not be known by many readers (including myself), and although a reference to another paper is provided,

this information should be included here. Figure 1 was updated with the extent of the domain similar to in Gerken et al 2013 (JGR) and Figure 3 now indicates topography.

Specific Figure comments

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- 1. Figure 1: This figure is key to orient the reader during the subsequent analysis, but is not very useful at the moment. I think the results in the paper can be applied beyond the Tibetan Plateau, so many readers may not be familiar with the region. At the moment it mainly shows land use type, but this is not referenced during the analysis at all (except land vs lake, of course). I would make the following suggestions: - The figure should show topography, as this is probably the most important forcing of convection. Either add this as a line contour, or replace the land use colour contours with topography. - Add a line showing the model domain. Also show what part of the model domain is the 'edge' - where fluxes are reduced to zero I assume this part is excluded from the subsequent analysis?) as well as which parts count as 'basin' and 'plain' (e.g. in figure 7). - Change the colour of the cross showing the location of the Nam Co station, as it is very hard to see. - In the caption: "the markers indicate 10km a.g.l..." I'm not sure what markers are being referred to here. - It would be helpful to label locations referenced in the text (e.g. the Nyenchen Thangla mountain chain). - either as an extra panel here, or in Figure 3, it would be useful to have a plot of topography along the model domain. Yes, the area, where fluxes are reduced to zero is not included in the analysis. The marker of 10 km agl refers to the small marker on the trajectory of the sounding. It shows the location, in which the sounding reached 10 km above ground level height. We improved the figure by adding the domain, increasing marker sizes and by adding additional labels. Figure 3 now shows the topography along the model domain.
 - 2. Figure 2: I suggest that the y-axis is changed to height agl, to be consistent with all the other figures. Figure 2 was changed according to the reviewer's suggestions.
 - 3. Figure 3: The axis and legend labels are too small. The colour contour range seems to wide, as I can only see light red/blue, so maybe this could be reduced? Maybe some

of the variability is hidden by the line contours. It would be clearer if the line contours were thinner (I can't see the w values inside). It is hard to distinguish the black and blue lines (either make the blue lighter, or remove the black lines and add a panel showing topography) Figure 3 was changed according to the reviewer's suggestions.

- Figure 5: Like in Figure 3, the blue and black are hard to distinguish, especially with so many lines. A lighter blue would be helpful. Figure 5 was changed according to the reviewer's suggestions.
 - 5. Figure 9: All labels need to be bigger. Figure 9 was changed according to the reviewer's suggestions.
- 6. Figure 10: It is quite hard to read this plot as it is quite small, especially the dashed line (maybe make this another colour?) Figure 10 (now 11) was changed in order to improve legibility, by increasing plot size, fonts and linewidths or colors.

Minor comments

1. P4636, L20: There is quite a large body of literature showing the effect of urface heterogeneity at those scales on winds and convection in aircraft observations (Taylor et al 2007, Garcia-Carreras et al 2010), satellite (Taylor et al 2012) and models (Cheng et al, 2004 amongst others). In particular, Taylor et al (2012) shows that, in flat terrain, a negative soil moisture - rainfall feedback appears to be the norm (consistent with the convectionpermitting simulations described in the following paragraph). We amended the introduction following the reviewer's suggestions (p14, L8-): "Taylor et al. (2012) showed that the likelihood of convective precipitation over wet soils was increased. This can potentially attributed to the development of mesoscale circulations between dry and wet patches. Clark et al. (2004) demonstrated that moisture variability on the 10 km scale can induce regional circulations that enhance convection. Additional evidence for the influence of soil moisture induced mesoscale circulations on convective

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development was found in observational (Taylor et al., 2007) and modelling studies (Cheng et al., 2004; Garcia-Carreras et al., 2010)."

2. P4643, L24: Here the authors are not using a single model grid point, but the model domain-mean, which will additionally introduce systematic differences due to heterogeneity in the domain(which the authors allude to earlier in the paper). How does Figure 5 change if the closest model grid point to the station is used, instead of the whole domain? Is 0.75 x FC still the 'best'? There is no need to necessarily show the figure, but a comment in the text would be useful. We believe that a 1:1 comparison between a single cell and the station is not meaningful, as the changes in exact cloud location, wind field etc during a single day, will have large effects on the simulated fluxes. In our opinion one would need more simulations (i.e a climatology or ensemble to get a meaningful comparison. We compared the fluxes for the grid cell closest to the eddyflux station. At this point the simulations that most closely matched the observed fluxes was 1.5 x FC in both terms of the Bowen-ratio and the decrease of fluxes in the afternoon due to cloud cover. The text was amended with (P 22, L9-): "A comparison between the grid cell closest to the station and measurements (not shown) indicates that case $1.5 \times \{FC\}$ matches most closely the observed fluxes in both terms of the Bowen-ratio and the decrease of fluxes in the afternoon due to cloud cover, but the timing of the decrease was too early."

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P4644, L10-11: This directly contradicts the 2D vs 3D comparison, which shows stronger convective development in the 3D simulation. In our opinion, this is not a direct contradiction to the previous statement, as we are talking first about the comparison of 2D and 3D simulations, while later we discuss the comparison between reality and 2D simulations. A lack of the third dimension will reduce entrainment and will thus increase convective strength. This is well established in the literature (i.e. Wu et al, 2009, Kirshbaum et al, 2011; cited in the manuscript).

Discussion Paper

"Technical" comments

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- 1. P4633, L11: I would change 'convection development' with either 'convective development' or 'development of convection' (here and elsewhere in the paper). changed to "convective development" througout the text
- 5 2. P4633, L14: "and sensible heat fluxes, WHICH has a strong..." changed
 - 3. P4634, L21: Remove 'semi-arid' (mountains are important triggers of convection everywhere). changed
 - 4. P4637, L21: "it is situated AT 300 m distance FROM a small lake... to the northwest BY a 500 m" **changed**
- 5. P4637, L24: "AT 00:00, 06:00 ..." technically radiosondes were not released at the times given, but circa 30 minutes before, as the the total time of the radiosonde ascent trough the topopshpere takes approximately 1 hour.
 - 6. P4640, L21: How come the simulation begins at 0400 LT while the initial profile is for 0600LT? Soundings were launched at standard meteorological times, while the model was started 2 hours before sunrise, to allow for the interaction of turbulence and atmospheric profiles, prior to starting the solar forcing. It was confirmed that the change in the mean profile was minimal during the two hours.
 - 7. P4641, L9: Use LT instead of UTC. changed to "06:00 LT (00 UTC)"
 - P4641, L17: What do T1 and T2 refer to? this refers to the two soil layers. Now (p19, L28) "first and second layer mean temperatures T1 andf T2"
 - 9. P4645, L14: "to soil moistures IN the moister 1.5 x FC case" changed
 - 10. P4646, L7-9: Unclear, suggest rewriting this sentence. Compared to the land surface, sensible heat fluxes from the water surface are small and have little variation between

cases. We clarify to: "There is little variation of evaporation from the lake surface between cases and total daytime evaporation is less than 0.5 mm (Fig. 6d) and thus 50 % smaller than evapotranspiration from the land surface of even the driest case, highlighting the role of the land surface as a source of water."

- 11. P4647, L8: "which is associated WITH INCREASED cloud cover". The following two sentences are unclear.' Thank you for pointing this out: In the editing process these sentences got garbled. We meant to express that after 12:00 the moist cases show a leveling off in exchanged surface energy, while the intermediate case, initially levels off, but then starts to increase again, which shows that due to decreased cloud cover surface fluxes pick up again. Now (p25, L29-f): "While there is also a reduction in fluxes after 12:00 LT, but unlike for the moister cases, this results in only a temporary reduction in the surface to atmosphere transfer of latent heat which then increases again, while the transfer of sensible heat is as large as for case 0.5 × FC."
 - 12. P4651, L22: Add a one sentence summary of the modelling approach (i.e. the fact that the model was run with a range of soil moistures). added (p 30, L17-): "The ATHAM model, with a fully coupled surface, was used to investigate surface-atmosphere interactions in a cross section through the Nam Co Lake basin for simulations with different initialized soil moistures."
 - 13. P4651, L4-6: move "only with very dry land surfaces" to the end of the sentence. changed
- ²⁰ 14. Figure 7 (caption): "sensible and latent energy over THE lake, over THE plain ... in THE total domain". **changed**
 - 15. Figure 8 (caption): replace 'cloud particle concentrations' with 'liquid water' (or whatever specific diagnostic is actually plotted) **changed**

Abstract

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²⁵ The Tibetan Plateau plays a significant role in the atmospheric circulation and the Asian mon-

soon system. Turbulent surface fluxes and the evolution of boundary layer clouds to deep and moist convection provide a feedback system that modifies the Plateau's surface energy balance on scales that are currently unresolved in mesoscale models. This work analyses the land surface's role and specifically the influence of soil moisture on the triggering of convection at a cross-section of the Nam Co Lake basin, 150 km north of Lhasa using a cloud resolving atmo-5 spheric model with a fully coupled surface. The modelled turbulent fluxes and development of convection compare reasonably well with the observed weather. The simulations span Bowenratios of 0.5 to 2.5. It is found that **convective** development is strongest at intermediate soil moistures. Dry cases with soils close to the permanent wilting point are moisture limited in the convective development, while convection in wet soil moisture cases is limited by cloud cover 10 reducing incoming solar radiation and sensible heat fluxes, which has a strong impact on the surface energy balance. This study also shows that local development of convection is an important mechanism for the upward transport of water vapour that originates from the lake basin that can then be transported to dryer regions of the plateau. Both processes demonstrate the importance of soil moisture and surface-atmosphere interactions on the energy and hydrological 15 cycles of the Tibetan Plateau.

1 Introduction

The Tibetan Plateau has an average elevation of more than 4500 m and is the world's largest mountain highland. Land-use/land-cover change such as permafrost (Cheng and Wu, 2007) and
grassland degradation or deforestation (Cui and Graf, 2009; Cui et al., 2006), but also effects on the carbon and hydrological cycles (Babel et al., 2014) are associated with overuse of resources and climate change. They also affect atmospheric circulation and hydrological resources of the Tibetan Plateau, especially the cryosphere (i.e. Yao et al., 2007; Ni, 2011; Kang et al., 2010; Yang et al., 2011, 2014). Effects on the hydrological cycle are likely enhanced due to changes
in phenology and length of the growing season (Shen et al., 2014; Che et al., 2014; Zhang et al., 2014). According to Immerzeel et al. (2010) more than 1.4 billion people in South-East Asia live in the catchments of rivers originating on the Tibetan Plateau. It is therefore important to

Surface–atmosphere interactions through the exchange of momentum, turbulent energy and water vapour play an important role in the development of convection and thus influence the energy balance of the surface and local precipitation. On the plateau scale the surface-energy balance impacts the plateau's role as an elevated heat source (i.e. Flohn, 1952; Gao et al., 1981; Yanai et al., 1992). This heating is probably not the main driver of the Indian monsoon system (Molnar et al., 2010; Boos and Kuang, 2010), but acts to modify it and influences regional atmospheric circulation as well as Eastern Asian precipitation (i.e. Liang and Wang, 1998; Zhou et al., 2004). While conventional atmospheric circulation models do not have a high enough resolution to resolve the relevant hydrological processes on the local scale, cloud-resolving models with a fully coupled surface model, as introduced by Patton et al. (2005), present a valuable tool for the systematic investigation of surface–atmosphere interactions, convective development

and locally generated precipitation.

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The triggering of deep convection over topography is a major source of precipitation in ([...]) mountainous environments (e.g Banta and Barker Schaaf, 1987; Gochis et al., 2004). The sum-15 mer monsoon season is associated with an increase of the total precipitable water in the atmosphere from approx. 5 to > 15 mm and a destabilisation of the atmospheric profile (Taniguchi and Koike, 2008). A diurnal cycle in cloud development leading to the triggering of local convection before noon is commonly observed on the Tibetan Plateau and is organised by thermal valley-circulations (i.e. Ueno, 1998; Ueno et al., 2009; Yatagai, 2001; Kuwagata et al., 2001; 20 Kurosaki and Kimura, 2002). This organisation of local circulation leads to daytime precipitation over mountain ridges and to night-time precipitation from convergence in the basin centre (Ueno et al., 2009). Modelling studies (Kuwagata et al., 2001) and remote sensing (Yatagai, 2001) have determined valley scales of $160-240 \,\mathrm{km}$ to be most effective for these processes. Yang et al. (2004) have also investigated thermal circulations on the Tibetan Plateau and found 25 secondary triggering of convection within Tibetan valleys as a result of cold-pool fronts caused by convective events that were triggered over the mountains. Similar effects were simulated for Nam Co Lake as the result of a combined lake-breeze thermal mountain circulation (Gerken et al., 2014). Uyeda et al. (2001) measured maximum cloud top heights of 17 kma.s.l. in the

Nagqu basin occurring between 12:00 and 15:00 LT. Yamada and Uyeda (2006) found different structures of convection and precipitation on the Tibetan Plateau, which were associated with dry and moist surfaces. Dry surfaces during the pre-monsoon led to a high cloud base and increased re-evaporation of precipitation, while moist surfaces during the monsoon yielded lower cloud bases and higher rates of deposited precipitation. A modelling investigation (Yamada, 2008) confirmed this process and showed stronger convective motion for the dry case. Hence, complex interaction of local and larger scale circulation with local environmental conditions are essential for the evolution of clouds and the hydrological cycle on the Tibetan Plateau.

The influence of the monsoon declines to the North on the Tibetan Plateau (Tian et al., 2001, 2003, 2007). At the same time local moisture recycling on the central plateau becomes essential 10 keeping the regional water cycle active (Kurita and Yamada, 2008). Their research highlights the importance of the boundary layer as a major source of the precipitated water during nighttime and of locally generated convection. Convection and precipitation at Nam Co Lake are both influenced by the lake's water body (Li et al., 2009) and the complex topography (Maussion et al., 2011, 2014).

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We previously investigated surface-atmosphere interactions, the development of mesoscale circulations and the evolution of convection in the Nam Co Lake basin. In Gerken et al. (2014) we applied a surface model (Gerken et al., 2012), coupled to the cloud-resolving ATHAM (Active Tracer High-resolution Atmospheric Model – Oberhuber et al., 1998; Herzog et al., 1998) and analysed convective triggering at Nam Co Lake. It was shown that the model can reproduce the most important atmospheric dynamics of the Nam Co Basin. Subsequently, the impact of different atmospheric profiles on convection and precipitation was investigated (Gerken et al., 2013a). These studies highlighted the importance of surface-atmosphere interactions in the generation of precipitation and convection.

Observed Bowen-ratios at Nam Co station vary from 3 to 0.5, with maximum latent heat 25 fluxes exceeding $400 \,\mathrm{Wm^{-2}}$ during wet conditions (Gerken et al., 2012). As a consequence Nam Co Lake can be classified as a semi-arid transitional region with strong soil moistureclimate coupling (Seneviratne et al., 2010). While the existence of feedbacks between landsurface moisture, rainfall and convective development is well known, there is disagreement on the dominating processes and the sign of the resulting feedback (Barthlott et al., 2011). Following the mechanism by Pal and Eltahir (2001), increased soil moisture increases the boundary layer's total convective available energy and lowers the lifting condensation level. Both increase moist convection. At the same time, decreased solar radiation input due to larger cloud cover can

- ⁵ reduce the available energy and thus convective development (Seneviratne et al., 2010; Pal and Eltahir, 2001; Pan et al., 1996). While soil-moisture atmosphere interactions occur on many different spatial and temporal scales, interactions on the seasonal scale are well documented (e.g. Fischer et al., 2007). Taylor et al. (2012) showed that the likelihood of convective precipitation over wet soils was increased. Interactions on shorter time scales are less well
- understood. Clark et al. (2004) has demonstrated that moisture variability on the 10 km-scale can induce regional circulations that enhance convection. Additional evidence for the influence of soil moisture induced mesoscale circulations on convective development was found in observational (Taylor et al., 2007) and modelling studies (e.g. Cheng and Cotton, 2004; Garcia-Carreras et al., 2010) Due to the localized convection triggering on the Tibetan
 Plateau, such processes might also play a role for precipitation at Nam Co Lake.

Compared to studies over flat terrain, much less is known about soil-moisture convection feedbacks above complex topography. Hohenegger et al. (2009) found a dependence on the model resolution in the Alpine region. Convection permitting resolutions led to predominantly negative feedbacks, caused by the presence of a stable layer above the boundary layer, while lower resolutions with parameterized convection showed positive feedbacks. Similarly, Barthlott et al. (2011) and Hauck et al. (2011) found considerable feedbacks between soil-moisture and precipitation, but with a variable sign of the feedback. They identified convective inhibition as a major cause.

It is, therefore, key to understand soil moisture precipitation dynamics and its feedbacks at Nam Co Lake and similar basins to gain a better understanding of the hydrological cycle on the Tibetan Plateau scale. This work investigates the role of the interactions between the lake, the surrounding basin with complex topography and the atmosphere in the development of boundary-layer clouds and their evolution into deep moist convection. We analyse (1) the sensitivity of **convective** development to surface moisture, (2) the modification of the surface energy-balance through feedbacks between surface-fluxes, specifically evapotranspiration, and cloud development and (3) the implications for locally triggered, convective precipitation at Nam Co Lake.

2 Material and methods

5 2.1 Site description

Nam Co Lake, approx. elevation 4730 ma.s.l., is located circa 150 km North of Lhasa and just to the North of the Nyenchen Thangla mountain chain, which has maximum peak heights of more than 7000 m. The average elevation of the Nam Co basin is 5230 m (Liu et al., 2010). Between 6 July and 6 August 2012 scientists from the University of Bayreuth conducted a field experiment at Nam Co Lake in cooperation with the Institute of Tibetan Plateau Research, Chinese 10 Academy of Sciences. The Nam Co Lake Monitoring and Research Station for Multisphere Interactions (Ma et al., 2009) is located at 30°46.44' N, 90°57.72' E. It is situated at 300 m distance from a small lake, which is divided from Nam Co Lake to the northwest through a 500 m wide land-bridge. The experiment is documented in Gerken et al. (2013b). Radiosondes were released on 8 days between 17 and 29 July for 00:00, 06:00 and 12:00 UTC. Eddy-covariance 15 flux measurements were performed with a CSAT-3 sonic anemometer and KH2O-Krypton Hygrometer (both Campbell Scientific). The KH2O was calibrated on site according to Foken and Falke (2012). Standard atmospheric and soil temperature as well as moisture measurements were also carried out.

As described in Gerken et al. (2014), the TK2/3 software package (Mauder and Foken, 2004, 2011) was used to post-process the high-frequency measurements. All flux corrections and post-processing steps recommended in Foken et al. (2012) and Rebmann et al. (2012) were applied to the flux data. Unlike surface models, the energy balance of eddy-covariance measurements is inherently unclosed (i.e. Foken, 2008; Foken et al., 2011). The presence of stationary, secondary
 circulations leads to a missing flux fraction of approx. 30 % at Nam Co Lake. Therefore, before comparing measured and modelled fluxes, it is necessary to correct eddy-covariances fluxes

according to the Bowen-ratio (Twine et al., 2000). Additional information about flux dynamics at Nam Co Lake can be found in Biermann et al. (2014). Vaisala RS92-SGP radiosondes on Totex-TA600 balloons were launched from a portable Vaisala sounding system with a mobile GPS antenna and signals were processed with the SPS-220 unit and DigiCora III MW21 software v3.2.1.

This work uses mean local time throughout, which is close to UTC + 6h or two hours before Beijing Standard Time. On 17 July sunrise, solar noon and sunset were determined with the National Oceanic and Atmospheric Administration Sunrise/Sunset Calculator as 23:05, 06:02 and 13:00 UTC.

- ¹⁰ The soil was characterized in 2009 (Biermann et al., 2009) and the vegetation classification was reassessed in 2012 (Gerken et al., 2014, see Table 1). Except for some wetlands close to the lake, the basin and surroundings of the station are sparsely vegetated and classed as alpine meadow and steppe (Mügler et al., 2010). Figure 1 shows the Nam Co Lake basin and includes the flight path of the radiosonde launched for 17 July **06:00 LT (00 UTC)**. The soil is estimated
- ¹⁵ to have little water retention capacity and a low permanent wilting point (PWP) at 2%. While the field capacity used for the modelling of 5% is very small, it is not unreasonably low for a sandy soil and produced good agreement of measured and simulated fluxes in Gerken et al. (2012).

2.2 Model description

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The non-hydrostatic, cloud resolving ATHAM model (Oberhuber et al., 1998; Herzog et al., 1998, 2003), used in this study has originally been developed to simulate volcanic eruption plumes (Graf et al., 1999). Subsequently, it was applied to biomass-burning plumes (e.g. Trentmann et al., 2006) and atmospheric applications (Guo et al., 2004). The model uses a *z* vertical coordinate, and can be run both in 2-D and 3-D mode. Tracers, including all hydrometeors, are active. This means that the density of the gas-particle mixture and heat capacity of the fluid are influenced by the local concentration of all tracers (Oberhuber et al., 1998).

The simulations in this work include the following physical processes, and are similar to the work in (Gerken et al., 2013a): Shortwave radiation (Langmann et al., 1998) and longwave

radiation (Mlawer et al., 1997), bulk-microphysics (Herzog et al., 1998). Turbulence closure is of 1.5-order and predicts both turbulent length scale and turbulent kinetic energy (horizontal and vertical) (Herzog et al., 2003). The modified Hybrid (v6) land surface model (Friend et al., 1997; Friend and Kiang, 2005; Gerken et al., 2012) and the Coupled Ocean–Atmosphere Response Experiment (COARE) – algorithm v2 (Fairall et al., 1996a,b) water surface scheme compute turbulent energy fluxes above land and water. Nam Co Lake has a mean depth of > 50 m (Wang et al., 2009). The surface model and the coupled system were shown to per-

form well for this site (Gerken et al., 2012, 2013a, 2014) and the reader is referred to these publications for a more extensive model description.

10 2.3 Model setup and cases

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Due to the almost parallel orientation of Nam Co Lake and the Nyenchen Thangla mountains, it is possible to simulate the system's most important dynamical features such as the diurnal cycle of turbulent fluxes, the formation of a lake-breeze and the interaction between locally generated clouds and the complex topography using a 2-D approach (Gerken et al., 2013a, 2014). Our model domain cuts across the lake, the Nam Co station, as location of our measurements, and through the Nyenchen Thangla mountain chain, which is of relatively low height at this location compared to the glaciated peaks in the Western range. The maximum elevation difference between the lake level and the mountain chain is approximately 800 m. As the 2-D modelling setup does not permit flow around the mountain chain, we expect to overestimate the influence of topography.

The 2-D domain used in this work has the same configuration as in Gerken et al. (2013a) with a total extent of 153.6 km divided into 770 grid points with a horizontal resolution of 200 m. There are 175 vertical layers with the first 50 layers at 50 m resolution and then stretching to resolution of 200 m, which is kept constant for the uppermost 50 model layers. The vertical domain extends to 17.5 kma.g.l. For the topography we use the 90 m resolution ASTER digital elevation model. While a 2 km moving window was used to smooth the topography within the basin, **convective** development has a negligible sensitivity to the window size as shown in the supplement to Gerken et al. (2013a). Outside the Nam Co basin the topography is set to the

same elevation as the lake. Surface energy fluxes are gradually reduced to zero in the vicinity of the horizontal boundary, as we are interested in the behaviour of the mountain-lake system enclosed by mountains and hills. In contrast to cyclic lateral boundary conditions for momentum, hydrometeor tracers and water vapour concentrations exceeding the initialized profile are

- ⁵ removed, without introducing a density perturbation. The 2-D simulations are integrated from 04:00 to 20:00. The model time-step is 2.5 s. To assess the suitability of the 2-D simulations, we compare the **convective** development in 2-D with a 3-D simulation of the cross-section that allows for the triggering of convection in three dimensions. The 3-D simulation spans the same domain in the principal horizontal and vertical dimension and is integrated over the first 12 h.
- ¹⁰ While the vertical resolution is identical to the 2-D simulations, the horizontal domain resolves the central 80 km and thus the lake basin and topographic elements at 200 m and then applies a grid stretching to span the total domain with a total of 490 grid points. The second horizontal dimensions spans 10 km with 200 m resolution and uniform topography in the *y*-direction. The lateral boundary in this dimension is fully cyclic.
- 17 July 2012 was selected as the basis for the investigations presented in this work as this day 15 was free of large-scale synoptic effects, which are not included in the model, and showed a characteristic evolution from clear sky with few boundary-layer clouds to locally generated Cumulonimbus activity. Gerken et al. (2013a) showed that the model realistically reproduced the observed weather and the evolution of the vertical profiles for temperature and moisture. Figure 2 displays the temperature and moisture profiles derived from the 00:00 UTC radiosounding 20 of 17 July. The initial RH of the atmospheric profile is reduced to a maximum of 90%. This is reasonable as there was no closed cloud cover at the time of the sounding so that cloud passages of a radiosonde would lead to an overestimation of relative humidities at the respective level. As the focus of this work is the investigation of the impacts of varying soil moisture, the initial geostrophic wind is set to 3 ms^{-1} throughout the model domain, which exhibited the 25 most realistic convection in Gerken et al. (2014). This also avoids wind shear to which 2-D simulations are very sensitive (i.e. Kirshbaum and Durran, 2004). The model was initialised with 6.8 and 2.6 °C as first and second layer mean temperatures $\overline{T_1}$ and $\overline{T_2}$, which corresponds to an initial surface temperature (T_0) of 4.5 °C. For the complete description of the

Hybrid surface model initialisation the reader is referred to Gerken et al. (2012). Soil moisture in the surface model is initialised as a fraction of field capacity (FC), which is the amount of water a soil can hold against gravity. In order to investigate the influence of soil moisture on convective development, we set the initial soil moisture of the simulations to 2.0, 1.5, 1.0, 0.75, 0.5 and $0.4 \times \{FC\}$. These cases are subsequently referred to by their initial soil moisture (e.g.

5 " $1.0 \times \{FC\}$ ").

While the $2.0 \times \{FC\}$ case corresponds to a realistic surface initialisation for 17 July, we leave soil temperatures and thus soil heat contents unmodified and reduce soil moisture gradually to the permanent wilting point ({PWP} = $0.4 \times {FC}$). The lake surface temperature is

initialised with 10° C, which is reported by Haginoya et al. (2009) as Nam Co Lake's mean

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3 **Results and discussion**

3.1 Comparison of 2-D vs. 3-D

surface temperature in July and August for 2006–2008.

While 2-D simulations of deep convective development are frequently used to investigate the triggering of convection (i.e. Wu et al., 2009; Kirshbaum, 2011; Garcia-Carreras et al., 2011), 15 they may overestimate convection due to the lack of entrainment in their convective plumes (e.g. Petch et al., 2008). As a consequence, we start the analysis by comparing the convective development for case $2.0 \times \{FC\}$ between the 2-D and 3-D simulations. As in Gerken et al. (2013a) we consider grid elements with liquid water contents (both water and ice) of $q_t > 1$ 10^{-3} gkg⁻¹ as clouds. 20

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Figure 3 shows the development of vertical velocities and cloud cover at several heights for 10:00 and 11:00 LT for the case $2.0 \times \{FC\}$ in the 3-D setup. During this time boundary layer clouds that form near the mountains and hills develop into a convective plume that reaches 9 kma.g.l. at 10:30 LT (not shown) and then develops further. Overall, this results in maximum updraft strengths in excess of $10 \,\mathrm{ms}^{-1}$. Subsequently, the cloud development in terms of cloud base height, cloud top height and centre of the cloud mass (Z_c) as defined by Wu et al. (2009):

$$Z_{\rm c} = \frac{\int \int q_{\rm t} z \, \mathrm{d}x \mathrm{d}z}{\int \int q_{\rm t} \, \mathrm{d}x \mathrm{d}z},\tag{1}$$

where z is the level and dxdz the integration area, are displayed in Fig. 4. We compare the 2-D case with the corresponding value of the 3-D simulation averaged over the additional dimension.
⁵ There is little difference in the cloud base height, while cloud top heights and Z_c for the 3-D simulation are slightly higher than in the 2-D case, indicating stronger convection. This is also reflected in the deposited precipitation. At the same time, the timing of the precipitation with two distinct peaks is similar between the two cases. This is somewhat counter-intuitive, as one would expect increased entrainment for the 3-D case and less strong convection. However
¹⁰ due to the topographic forcing clouds are organised in bands so that entrainment is of less importance than anticipated. Our results are comparable to Garcia-Carreras et al. (2011), who also had stronger cloud development in the 3-D case. This might be due to the absence of lateral entrainment of dry air due to the limited extent and cyclic nature of the third dimension.

Despite some differences in the structure of convective evolution, the resulting convective development is sufficiently similar to focus on a 2-D approach to further evaluate the behaviour of the system.

3.2 Turbulent fluxes

We investigate the locally driven evolution from boundary-layer clouds to precipitating convection as is frequently observed at Nam Co Lake. Variation of initial soil moisture contents in Hybrid leads to a shift in the Bowen-ratio. Figure 5 displays the diurnal cycle of the simulated median turbulent latent (Q_E) and sensible heat fluxes (Q_H) as well as incoming solar radiation (SWD). The last panel shows the observed quantities at Nam Co station. As expected, the Bowen-ratio changes from approx. 2.5 for the dry surface at PWP to 0.5 for the moist surface at $2.0 \times {FC}$. While the incoming solar radiation initially follows the clear sky radiation, there is a reduction of downward shortwave radiation seen in both the simulations and the measured fluxes after solar noon. This decrease in incoming solar radiation is strongest for $1.0 \times {FC}$,

while $1.5 \times \{FC\}$ and $2.0 \times \{FC\}$ show a slightly weaker decline during the afternoon. This highlights the impact of soil moisture on cloud development. Larger latent heat fluxes lead to increased cloud formation, which is further discussed in the next sections. Solar radiation and surface fluxes were measured at Nam Co station, while the surface model calculated surface fluxes are for the total model domain. Due to the stochastic nature of turbulence, it is 5 not meaningful to directly compare a single model grid-cell to the measured data. However, it is possible to say that the median, simulated solar radiation flux within the Nam Co basin for case $0.75 \times \{FC\}$ resembles most closely the measurements, while the moister cases have lower simulated solar irradiation. A comparison between the grid cell closest to the station and measurements (not shown) indicates that case $1.5 \times \{FC\}$ matches most closely the 10 observed fluxes in both terms of the Bowen-ratio and the decrease of fluxes in the afternoon due to cloud cover, but the timing of the decrease was too early. At the same time there is large variation of fluxes as indicated by the interquartile difference, so that simulated solar radiation flux for all cases appears to be in reasonable agreement with the measured shortwave radiation.

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The spatial variability of surface energy fluxes and solar radiation also demonstrates that surface atmosphere interactions change with increasing soil moisture. With the onset of cloud development, solar irradiance of shaded grid cells begins to drop, while the median irradiance and turbulent surface fluxes remain unaffected. With increasing cloud optical depth median shortwave radiation fluxes begin to decrease. This occurs first in 20 the most shaded cells and then progresses to the mean fluxes. For the moister simulations $(1-2 \times \{FC\})$ there is little difference between lower and upper quartile latent heat fluxes in the early afternoon, indicating widespread cloud cover as the main driver for the decrease. However, in the later afternoon, there is again increased variability in the simulated turbulent fluxes (both median and upper quartile) that is not accompanied with 25 a corresponding increase in the median solar irradiation flux. This indicates that in addition to solar irradiance, local circulation systems likely play a role in the surface energy balance. The impact of local circulations on the surface energy balance, turbulent fluxes and convective triggering was investigated in Gerken et al. (2014).

Eddy-covariance measurements have a footprint area of similar magnitude as ATHAM's grid cells. Nevertheless, the same problem of comparing point measurements to a distributed simulation applies. Overall, there is a general agreement in the diurnal development of fluxes, with a decrease of turbulent fluxes in the afternoon. Case $2.0 \times \{FC\}$ corresponds to a realistic surface initialisation. A comparison of simulated and measured fluxes in Fig. 5f and g shows that 5 measured median simulated fluxes in the afternoon are lower than the measured ones, while the maximum fluxes around noon show similar magnitudes. This is likely due to an overestimation in the simulated **convective** development that is caused by the lack of the third dimension and entrainment of dry air into convective thermals. The inherently unclosed nature of turbulent fluxes measured by the eddy-covariance technique (Foken, 2008) introduces an additional de-10 gree of uncertainty into the comparison of modeled and measured fluxes. The observed mean of the ground heat flux at the Nam Co station is in the order of 30 % of net radiation (Biermann et al., 2014), leaving approximately 30% of the total surface energy balance unclosed. Using the energy balance correction of Twine et al. (2000) conserves the observed Bowen-ratio, while the recently proposed buoyancy correction according to Charuchittipan et al. (2014) would at-15 tribute most of the unclosed flux to $Q_{\rm h}$ and would thus change the Bowen-ratio considerably. The Hybrid surface model was able to reproduce turbulent flux measurement at the Nam Co station for a wide range of observed soil moistures (Gerken et al., 2012). Additionally, Kracher et al. (2009) showed that many land surface models tend to reproduce measured Bowen-ratios. As a consequence, we assume in this work that the Bowen-ratio method of energy balance clo-20 sure (Twine et al., 2000) is applicable and that there is an overall reasonable agreement between the diurnal evolution of modelled fluxes for the moister surface initalisations and the measured fluxes.

3.3 Soil moisture – evapotranspiration response

Immediately connected to turbulent flux dynamics and of central importance for the hydrological response of the Nam Co basin is the question of the relationship between soil moisture and evapotranspiration. Figure 6 displays the soil moisture variables for the simulated cases. The first panel shows the development of soil moisture expressed as a function of field capacity for the upper model layer. From Fig. 6 it becomes apparent that evapotranspiration during **the daytime** has a large effect on modelled soil moisture. The surface model Hybrid has a comparatively simple treatment of soil moisture, which includes drainage, molecular diffusion between soil layers for transport and evapotranspiration and precipitation as sources and sinks. While there is a general decreasing tendency of soil moisture during the course of the simulations,

precipitation events can replenish the soil with water. In the case of $1.0 \times {FC}$, afternoon precipitation leads to soil moistures in the upper layer that are slightly larger than the initialised soil moisture and similar to soil moistures as in the moister $1.5 \times {FC}$ case.

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Simulated evapotranspiration is expected to show a strong dependency on soil moisture for the relatively dry cases. Indeed there is a large increase in simulated evapotranspiration between 10 cases $0.5 \times \{FC\}$ and $0.75 \times \{FC\}$, demonstrating a soil moisture limited regime as discussed in Seneviratne et al. (2010). A further doubling of soil moisture to $1.5 \times \{FC\}$ leads to a similarly big increase in evapotranspiration. This increase, however, is no longer true for the case $2.0 \times \{FC\}$, which in fact has a lower actual evapotranspiration than the $1.5 \times \{FC\}$ case. Between these two cases, the surface has switched from a moisture limited regime to a radiation 15 limited one due to an additional increase in cloud cover. At the same time, estimated potential evapotranspiration peaks for the $1.0 \times \{FC\}$ case (Fig. 6c). Potential evapotranspiration, as calculated in Hybrid, is unlike the other quantities not a standard model output and had to be estimated with 5 min averaged model outputs, leading to some uncertainties in its magnitude. Nevertheless, it is striking that $1.0 \times \{FC\}$ has the largest potential evapotranspiration, while 20 $1.5 \times \{FC\}$ and $2.0 \times \{FC\}$ as the moistest cases in fact have the lowest. Additionally, for case $1.5 \times \{FC\}$ actual evapotranspiration approaches potential evapotranspiration. In addition to the transition from a soil moisture limited to a radiation limited regime, there is also a feedback evident between soil moisture and **convective** development, which acts trough the generation of wind, precipitation and the reduction of incoming shortwave radiation. This will be further 25 discussed in Sect. 3.4.

There is little variation of evaporation from the lake surface between cases and total daytime evaporation is less than 0.5 mm (Fig. 6d) and thus 50 % smaller than evapotranspiration from the land surface of even the driest case, highlighting the role of the land

surface as a source of water. Additionally, the lake does not exhibit a strong diurnal pattern in simulated evaporation. This is in reasonable agreement to Biermann et al. (2014), who did not find a diurnal cycle in the measured lake evaporation.

- Figure 7 shows the importance of soil moisture for the energy balance of the Nam Co basin.
 Turbulent surface fluxes are integrated over space and time. The surface energy-balance on the Tibetan Plateau is of key importance for understanding hydrological processes. Due to the clean atmosphere (i.e. Cong et al., 2009) at Nam Co Lake and its high elevation, the fraction of diffuse to direct radiation is small compared to more polluted environments so that clouds, through modification of the net radiation, have a stronger influence on the surface energy balance than in
- other regions. Soil moisture strongly modifies the partitioning of the available energy into sensible and latent heat, evident in the Bowen-ratio, and thus the surface energy balance. We separated the integrated surface energy fluxes into the area of the lake, the non-elevated land around the lake, referred to as *plain*, the Nam Co basin, which is defined from the lake to the top of the Nyenchen Thangla and an equal extent on the northern side of the lake. For
- completeness the whole domain values are also presented. Overall, sensible heat fluxes from the lake are negligible, while the importance of Nam Co Lake for latent energy fluxes compared with the plain-area is very dependent on the initial soil moisture conditions: for the cases PWP and 0.5 × {FC} integrated latent heat fluxes from the lake have almost the same magnitude as the fluxes from the plain area, whereas for the moister cases they are comparatively small.
 As a consequence the importance of the lake as a moisture source for the surrounding area decreases with moister environmental conditions.

In general, there is a rather complicated behaviour of integrated energy fluxes for the plain and the basin area, which must be attributed to local dynamics such as the lake breeze, cloud cover and the evolution of convection. $1.5 \times \{FC\}$ has the largest transfer of latent energy from the land surface to the atmosphere, while the moister $2.0 \times \{FC\}$ case has a smaller transfer of both latent and sensible energy. After 12:00 LT there is a visible change in the slope for $2.0 \times \{FC\}$, which is associated with increased cloud cover, while a similar kink for $1.5 \times \{FC\}$ and $1.0 \times \{FC\}$ is less strong. For $0.75 \times \{FC\}$ there is a different behaviour. While there is also a reduction in fluxes after 12:00 LT, but unlike for the moister cases, this results in only

a temporary reduction in the surface to atmosphere transfer of latent heat which then increases again, while the transfer of sensible heat is as large as for case $0.5 \times \{FC\}$.

3.4 Convective development

We investigated the development of locally developed convection as it is frequently observed in the Nam Co Lake basin. As discussed in Sect. 3.2 there is a direct interaction between soil moisture, Bowen-ratio and turbulent surface fluxes, which to a large extent drives convective evolution. Therefore, differences in convective development are expected for the simulated cases.

During the course of the day, boundary-layer clouds forming at the beginning of the simulation grow into moist deep convection that produces precipitation in the model domain. Figure 8 displays the simulated averaged cloud liquid water concentration, as well as Z_c , cloud **base** and cloud top height. While all simulations lead to the development of deep convection, there are some differences in the amount of generated convection, the convective timing and dynamics as well as deposited precipitation (Sect. 3.5). The drier PWP and $0.5 \times {FC}$ cases show only limited or isolated convection before solar noon and then some deeper convection around 14:00, which does not lead to strong precipitation. Cases $0.75 \times {FC}$ and $1.0 \times {FC}$ on the other hand have a slightly stronger and earlier triggering of convection and then a stronger release of convective energy in the afternoon that is accompanied with a distinct precipitation event. The moistest simulations (Cases $1.5 \times {FC}$ and $2.0 \times {FC}$) have a stronger cloud development before noon and then lack a strong convective triggering in the afternoon.

These three regimes become especially visible, when analysing the convective massflux M_c defined as the product of moist density (ρ) and vertical velocity (w) integrated for a given height z:

$$M_{\rm c}(z) = \int \rho w \,\mathrm{d}A,\tag{2}$$

and integrated over cloudy grid cells with w > 0 (Fig. 9). Cases $0.75 \times \{FC\}$ and $1.0 \times \{FC\}$ are the only simulations that show a peak in convective massflux in the afternoon at 5 km and

7 kma.g.l., while the remaining simulations show a different evolution. As the development of deep convection is sustained by the release of latent energy, it is expected to gain strength with height until latent energy release becomes smaller than the reduction of buoyancy by the entrainment of dry air. Overall, there is little difference in M_c at 3 km between the cases, but the dry cases lack the moisture for a subsequent release of latent energy and strong convection

- ⁵ the dry cases lack the moisture for a subsequent release of latent energy and strong convection in the afternoon. It should be noted that the initial profile is quite moist for the lowermost 3 km, but then there is a dry zone between 3 and 6 kma.g.l. The equivalent potential temperature profile (θ_e) reveals a predisposition for convection. Hence, comparatively large Q_E fluxes are necessary to provide the atmosphere with sufficient moisture for the development of convection
- and the release of latent heat. At the same time, the moister simulations also do not develop strong deep convection, as they have the smallest convective massflux at 3 km around 14:00 LT. This means that the cloud cover displayed in Fig. 8e and f develops earlier and is not associated with strong convective motion. At the same time, the cloud base height decreases with increasing moisture as more water vapour accumulates in the the boundary layer, which is consistent
 with the investigation by Golaz et al. (2001) and Yamada (2008), who also found a decreased
- buoyancy for their wet surface case. Furthermore, for the intermediate cases, local differences in precipitation affect surface moisture and potentially induce circulations that lead to additional convection triggering (Clark et al., 2004).

An analysis of convective available potential energy (CAPE) tells a similar story (Fig. 10).
After sunrise, simulated CAPE-values in the Nam Co start to diverge between cases due to differences in the surface energy balance. Cases PWP and 0.75 × {FC} develop the least amount of CAPE, which is fully released between 9:00 LT and 14:00 LT. The moistest cases in contrast develop the largest amounts of CAPE, but it is not fully released as high soil moistures and associated lack of sensible heat fluxes reduce convection development. Consequently, CAPE is exported from the basin. Cases 0.75 × {FC} and 1.0 × {FC} present an intermediate, for which there is ample development of CAPE, which is almost fully depleted by convection during the afternoon, so that they have the highest overall release

of CAPE. Overall, there are three different regimes of convective development in the simulations for

Nam Co Lake that are associated with soil moisture. As convective development requires the availability of moisture and vertical instability through surface heating these conditions are best met for the intermediate moisture cases, while the drier cases do not provide a strong enough moistening and the moister cases inhibit the development of vertical motion due to increase cloud cover and lack of surface heating.

3.5 Precipitation and atmospheric moisture transport

The development of convection at Nam Co Lake is associated with daytime precipitation. Several studies have addressed the mechanisms of precipitation development in Tibetan valleys (e.g. Kurita and Yamada, 2008; Ueno et al., 2009). In addition to precipitation from mesoscale convective systems there are two types of locally developed precipitation: (1) daytime isolated convection triggered over the mountain chains or, in the case of Nam Co Lake, at the collision front between the lake-breeze and the geostrophic wind (Gerken et al., 2013a) and (2) convergence in the centre of the valleys through thermal circulations leading to nighttime precipitation. Due to the nature of our study, we only discuss the effects of locally generated, daytime precipitation.

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As was demonstrated in Sect. 3.3 locally generated precipitation has a large influence on the availability of soil moisture and thus on surface fluxes. This is of special importance since potential evaporation rates of approx. $4 \,\mathrm{mmd}^{-1}$ are of similar magnitude as the water that is stored in the uppermost 10 cm of the soil at field capacity. Actual evaporation rates for a Kobresia meadow were measured at 2 to $6 \,\mathrm{mmd}^{-1}$ (Babel et al., 2014). Therefore, the water balance of the Nam Co basin and the regional transport of water vapour are of importance. Due to the simple Kessler-type microphysics used in this study, the actual precipitation rates only allow for a qualitative comparison between cases.

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Table 2 displays the deposited precipitation for the convection simulations in terms of absolute mass and as fraction of evapotranspiration. For the entire domain between 6 and 10% of the evapotranspirated moisture is deposited as precipitation. These values are smaller than commonly reported. This is at least partially due to the integration time of our simulations, which is shorter than the typical residence time of atmospheric water vapour. The lake surface has the

largest spread with 1 to 44 % of recycled water. In general, the lake surface receives comparatively less precipitation per area than the rest of the basin, which is in line with expectations, as a cool water body suppresses convective activity. We observe increasing precipitation with increasing soil moisture. This trend is most clear for the driest cases, while it becomes less apparent for the moistest cases. This is in accordance to the observations of convective activity, which are strongest for intermediate initial soil moistures. Additionally, the basin and the plain are over-represented in terms of deposited precipitation in comparison to the total domain.

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A closer investigation into the moisture budget of the Nam Co Lake basin (Fig. 11) further points to the importance of vertical moisture transport within the region. We define two control

- domains for the Nam Co basin: control domain A corresponds to the lowermost 3 kma.g.l., while control domain B is is located directly above and extends to 10 km. The horizontal extent of the control domains is from the centre of the model domain to the top of the Nyenchen Thangla mountain chain and a similar extent to the north-west (see also Fig. 11g for illustration). It becomes apparent that the vertical transport of moisture dominates the overall moisture
- ¹⁵ budget of both control **domains** for all displayed simulations, while evapotranspiration and precipitation are comparatively small terms. This leads to a net decrease of moisture in the lower control **domain** A during the daytime. During the nighttime a reversal of the thermal circulation and subsidence should lead to a balancing of the moisture budget, which is not included in our simulations. Table 3 presents the full moisture balance for all cases. The convective
- ²⁰ transport from **domain** A to **domain** B is strongest for $0.75 \times \{FC\}$ and $1.0 \times \{FC\}$, while the remaining cases are of similar magnitude, underpinning again the preferential **convective** development for intermediate soil moistures. Lateral moisture transport, or advection is of only small importance for the lower control **domain** as the net flux is small. Vertical moisture transport dominates for **domain** A and it is the primary source of moisture for **domain** B. In the
- ²⁵ afternoon, when convective activity ceases, the moisture budget of the upper **domain** becomes increasingly more dominated by lateral transport of moisture with the background wind. This signifies that clouds and water vapour are removed from the basin, indicating locally occurring convection as a source of moisture for the larger region. However, as previously mentioned, the upper level wind speeds used in this work are unrealistically low, so that under realistic condi-

tions one would expect an even faster transport of moisture from the basin to the surrounding area. Recent work by Froidevaux et al. (2013) investigated the importance of background wind speeds and horizontal transport of convective cells during their development. While wind speeds used in this work were lower than observed, the lake-land circulation (i.e. Gerken et al., 2014) provides the necessary horizontal propagation mechanism that allows for the development of convective cells.

4 Conclusions

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In this work we have used the high-resolution atmospheric model ATHAM, coupled with the Hybrid surface model, to investigate the influence of soil moisture on convective development in the Nam Co Lake area. Surface moistures and, thus, turbulent fluxes are highly variable on the Tibetan Plateau and are therefore not only important for the Bowen-ratio and the surface energy balance, but also have an effect on atmospheric dynamics.

It was established in this work as well as in previous studies that the modelling system used in this investigation is a sensible and cost effective approach for the most important processes with regard to surface–atmosphere interactions, the evolution from boundary-layer clouds to deep and moist convection, and its interaction with background winds and complex topography.

The ATHAM model, with a fully coupled surface, was used to investigate surfaceatmosphere interactions in a cross section through the Nam Co Lake basin for simulations with different initialized soil moistures. The model produces realistic turbulent energy fluxes of latent and sensible heat. The reduction in surface moisture leads to a shift in the Bowen-

- ²⁰ of latent and sensible heat. The reduction in surface moisture leads to a shift in the Bowenratio from 0.5 to 2.5. The fluxes of the most realistic surface configuration are in reasonable agreement to measured fluxes at Nam Co station. There is a feedback between surface fluxes, cloud cover and convection. Larger latent heat fluxes lead to increased cloud cover and consequently to smaller net surface radiation. This is seen in the simulated evapotranspiration. The surface abanges from a unter limited to a radiation limited aupotranspiration ragime so that
- ²⁵ surface changes from a water limited to a radiation limited evapotranspiration regime, so that increased moisture actually means smaller net surface radiation. The role of the lake as a source of moisture depends on the initial surface moisture. Latent heat fluxes from the lake have

a substantial contribution to the overall water budget of the basin only for very dry landsurfaces. Our research clearly demonstrates the importance of soil moisture for the overall surface energy-balance of the lake system and thus for potentially wider implications for the Tibtean Plateau's energy balance as a whole.

⁵ We subsequently investigated convective development and convective mass-fluxes and found a "convective optimum" for the Nam Co Lake basin at intermediate soil moistures. At small soil moistures there is insufficient moisture available for latent heat release, which drives convection in the conditionally unstable Tibetan atmosphere. At very high soil moistures there is increased cloud cover, small sensible heat fluxes and decreased vertical motion. So while precipitation does occur, there is little convective development.

This has implications for the moisture budget of the Nam Co basin. We found that the basin itself and especially the plain and the mountains are a preferential area for precipitation so that weather stations close to the lake are not representative for the entire basin. At the same time vertical transport of moisture through convection and the subsequent lateral transport with the background wind, may be an important water source for the larger region. Overall, precipitation 15 effects can be directly seen in the soil moisture response of the coupled model and thus have an influence on turbulent fluxes, convective development and the surface energy balance. As precipitation events are both small in scale and short in duration, it is extremely important to get a good representation of regional precipitation in time as well as location. This requires mesocale models at the appropriate resolutions in the order of a few hundred meters. Addition-20 ally, both Hohenegger et al. (2009) and our previous work (Gerken et al., 2013a) highlight the importance of atmospheric profiles, through stability and convective inhibition, in the triggering of convection. This demonstrates a further need for accurate high resolution data-sets for soil and atmospheric data.

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As current environmental impacts such as climate change and land-use change are expected to not only impact surface cover and soil moisture, it is important to assess, how these changes will affect **convective** development and thus the hydrological cycle on the Tibetan Plateau.

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Fig. 1: Figure Updated – Land-use map of Nam Co Lake created from Landsat data. The yellow line shows the path of radiosonde ascent on 17 July 2012, 00:00 UTC. The yellow circle indicate the location at which the radiosonde reaches 10 km a.g.l. and the cold-point height. The cyan cross indicates the location of Nam Co station. The inset, reproduced from Gerken et al. (2012), shows the area near the small lake and the location of Nam Co Station (NamITP). {} 2012, The Microsoft Corporation, {} Harris Corp, Earthstar Geographics LLC.



Fig. 2: Figure updated – Initial profile for Nam Co Lake 17 July 2012 06:00 LT used in the model simulations as measured by radiosonde. (a) Potential (θ), equivalent potential temperature ($\theta_{e,sat}$); (b) Temperature (T) and dew-point temperature (T_{dew}) and (c) mixing ratio (q).



Fig. 3: Figure updated – Development of convection in the three dimensional simulation of case $2.0 \times \{FC\}$ at 10:00 LT for heights 1, 3, 5, 7 and 9 kma.g.l. (a–e); at 11:00 (g–k). The filled contours indicate vertical velocities (w, [ms⁻¹]) and the red contour lines show the location of clouds; (f+l) display the topography of the model domain. The location of the lake is indicated by the blue line.



Fig. 4: Comparison between the 2-D and 3-D simulation of case $2.0 \times \{FC\}$ for (a) cloud base height; (b) cloud top height; (c) the centre of cloud mass (Z_c as defined in text) and (d) mean deposited precipitation.



Fig. 5: Figure updated – Development of turbulent surface fluxes in the Nam Co Lake basin for cases PWP, $0.5 \times \{FC\}$, $0.75 \times \{FC\}$, $1.0 \times \{FC\}$, $1.5 \times \{FC\}$ and $2.0 \times \{FC\}$ on 17 July 2012 (a–e) respectively. Thick black lines correspond to the median flux over land. For SWD and Q_E also the upper and lower quartiles are given as thin lines, presenting a measure of spatial flux variation. The dashed line is clear sky SWD; (g) measured turbulent fluxes near Nam Co research station. Thin lines correspond to directly measured eddy-covariance fluxes. Thick lines are energy-balance corrected fluxes according to Twine et al. (2000).



Fig. 6: Moisture variables over time and averaged for Nam Co basin for cases PWP, $0.5 \times \{FC\}$, $0.75 \times \{FC\}$, $1.0 \times \{FC\}$, $1.5 \times \{FC\}$ and $2.0 \times \{FC\}$ on 17 July 2012: (a) soil moisture in terms of $\{FC\}$ [–]; (b) integrated evapotranspiration [mm]; (c) integrated potential evaporation [mm] and (d) integrated evaporation from Nam Co Lake [mm].



Fig. 7: Spatially and temporally integrated turbulent energy fluxes (*E*) at Nam Co Lake for cases PWP, $0.5 \times \{FC\}$, $0.75 \times \{FC\}$, $1.0 \times \{FC\}$, $1.5 \times \{FC\}$ and $2.0 \times \{FC\}$ on 17 July 2012: (**a** and **b**) Sensible and latent energy over **the** lake, (**c** and **d**) over **the** plain adjacent to **the** lake, (**e** and **f**) the Nam Co basin as defined in the text and (**g** and **h**) in total domain.



Fig. 8: Figure updated – Modeled development of convection at Nam Co Lake for cases PWP, $0.5 \times \{FC\}$, $0.75 \times \{FC\}$, $1.0 \times \{FC\}$, $1.5 \times \{FC\}$ and $2.0 \times \{FC\}$ on 17 July 2012: contours correspond to mean cloud water equivalent concentrations in the Nam Co Lake basin $[gm^{-3}]$. The dashed line indicates the height of the center of cloud mass (Z_c) and black lines indicate cloud top and cloud bottom heights. The upper panel of each subplot indicates mean deposited precipitation within each 5 minute interval $[gm^{-2}]$.



Fig. 9: Figure updated – Convective massflux at 3, 5 and 7 kma.g.l. for cases PWP, $0.5 \times$ $\{FC\}, 0.75 \times \{FC\}, 1.0 \times \{FC\}, 1.5 \times \{FC\} \text{ and } 2.0 \times \{FC\} \text{ on } 17 \text{ July } 2012.$



Fig. 10: New Figure – Temporal development of simulated Convective Available Potential Energy (CAPE, [Jkg⁻¹]) within the Nam Co Lake basin for cases PWP, $0.5 \times \{FC\}$, $0.75 \times \{FC\}$, $1.0 \times \{FC\}$, $1.5 \times \{FC\}$ and $2.0 \times \{FC\}$ on 17 July 2012.



Fig. 11: Figure updated – Instantaneous moisture flux $f_q [kgm^{-1}s^{-1}]$ for Nam Co Lake basin. (a, c and e) Moisture transport into control volume A, as indicated in panel (g) of this figure, representing the Nam Co basin up to 3 kma.g.l.: evapotranspiration (blue); precipitation (cyan); net horizontal flux (black); net vertical flux (red) and resulting total flux (grey, dashed). The precipitation flux is not displayed as it is of negligible magnitude. (b, d and f) Transport into the mid-tropospheric control volume B with the same horizontal extent and from 3 to 10 km vertical extent; (g) is a schematic drawing of the control volumes.

Table 1: Description of the soil and surface parameters at Nam Co station $(30^{\circ}46.44' \text{ N}; 90^{\circ}57.72' \text{ E})$ and which are also used for the simulations. LAI and vegetation height were estimated for July 2012 (Biermann et al., 2009). The table is modified from Gerken et al. (2013a).

Parameter	
Texture	sandy
Porosity	0.39
Field Capacity	0.05
Wilting Point	0.02
Heat capacity (c_p) [Jm ⁻³ K ⁻¹]	2.2×10^6
Thermal	0.20
Conductivity $[Wm^{-2}K^{-1}]$	
Surface Albedo (α)	0.2
Surface Emissivity (ϵ)	0.97
Vegetated Fraction	0.6
$LAI [m^2 m^{-2}]$	0.6
Vegetation height [m]	0.07

Table 2: Total simulated deposited precipitation (Prec, $[gm^{-2}]$) and normalised by evapotranspiration ($\{Prec\}/\{ET\}[-]$) for cases PWP, $0.5 \times \{FC\}$, $0.75 \times \{FC\}$, $1.0 \times \{FC\}$, $1.5 \times \{FC\}$ and $2.0 \times \{FC\}$ on 17 July 2012 for lake area, the plain adjacent to lake, the Nam Co basin as defined in the text and the total domain. The area definitions are the same as used in Fig. 7.

Case	Lake		Plain			Do	
	Prec	$\{\operatorname{Prec}\}/\{\operatorname{ET}\}$	Prec	$\{\operatorname{Prec}\}/\{\operatorname{ET}\}$	Prec	$\{\operatorname{Prec}\}/\{\operatorname{ET}\}$	Prec —
	$[\mathrm{gm}^{-2}]$	[-]	$[\mathrm{gm}^{-2}]$	[-]	$[\mathrm{gm}^{-2}]$	[-]	$[gm^{-2}]$
PWP	6	0.01	115	0.09	103	0.10	65 65
$0.5 \times \{FC\}$	5	0.01	81	0.06	154	0.13	74 Us
$0.75 \times \{FC\}$	55	0.11	224	0.11	194	0.12	103 0
$1.0 \times \{FC\}$	40	0.08	244	0.12	393	0.24	204 🗒
$1.5 \times \{FC\}$	47	0.09	315	0.11	176	0.09	153 원
$2.0 \times \{FC\}$	216	0.44	355	0.14	271	0.15	201

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Table 3: Total integrated moisture flux (F_q) into Nam Co Lake basin between 06:00 and 16:00 BST. The control **domains** denoted with subscripts A and B are indicated in Fig. 11g). The subscripts {Nw}, {Se} for the northwest and southeast boundaries. Positive fluxes across the lateral boundaries indicate flux into the domain. {ET} and P are the evapotranspiration and precipitation flux. 3 and 10 indicate the vertical boundaries of the control volumes, with a negative sign for upward flux. Δq_{tot} is the total net moisture flux for a volume.

	Volume A								-	
					Volume B)isc
Case	$F_{\{q,ANw\}}$	$F_{\{q,ASe\}}$	$F_{\{q,ET\}}$	$F_{\mathbf{q},P}$	$F_{q,3}$	$F_{\rm q,10}$	$F_{\{q,BNw\}}$	$F_{\{q,BSe\}}$	$\Delta q_{\{\text{tot},A\}}$	Δq_{ft}
		[Mg]				[Mg]		[Mg]	SIO
PWP	1351.8	-1382.4	51.4	-5.2	99.3	-2.3	244.3	-332.1	-83.7	
$0.5 \times \{FC\}$	1367.1	-1360.9	57.6	-7.8	128.4	-3.9	279.4	-350.3	-72.4	ar J
$0.75 \times \{FC\}$	1473.4	-1449.0	79.4	-9.8	166.3	-9.5	181.7	-332.8	-72.4)er
$1.0 \times \{FC\}$	1438.7	-1438.0	81.9	-19.9	167.1	-0.1	256.0	-372.8	-104.4	
$1.5 \times \{FC\}$	1432.8	-1430.0	103.2	-8.9	124.7	-3.4	324.2	-355.6	-27.6	
$2.0 \times \{FC\}$	1422.6	-1417.0	90.5	-13.7	129.7	-6.5	334.8	-366.4	-47.3	E

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