Author response

General response

First, we would like to thank the four anonymous referees for their helpful and thoughtful comments, remarks and suggestions. We are sure that these will help to improve the manuscript. We will add a description of validation and evaluation conducted for HAR to a revised version of the manuscript. We will carefully revise the whole manuscript to improve its structure and language. We revised some of the sentences marked as being grammatically incorrect by the reviewers. Since we have to rephrase parts of the manuscript during the process of revision, we cannot promise that we will not have to change them again, and want to make the reviewer and editor aware of this possibility. The reviewer comments are highlighted in black, while our responses are highlighted in blue. We numbered the reviewer comments to make it easier to refer to a response to a specific comment later in the author response. R1C1, for example, stands for reviewer 1, comment 1.

Anonymous Referee #1

Received and published: 8 March 2016

Overview –

This manuscript investigates the influence of dynamic factors on precipitation in High Asia. Findings on the seasonality and spatial variability of precipitation controls (and precipitation type) in the region using horizontal and vertical wind speed, atmospheric water transport, and boundary layer height are an important contribution to the field. The research is presented in an intuitive manner and uses unique data to answer major questions that have not been previously addressed. I do have a few questions/concerns about the applicability of HAR, and am suggesting considerable revisions, but after these issues are addressed I believe the manuscript will be fit for publication.

General Comments –

R1C1: HAR is a great data source that can help us address many questions that could not previously be asked in High Asia, but there are still many issues in modeling precipitation (especially convective precipitation) using 10km resolution with a convective parameterization. Rather than discourage the use of these unique data, I believe it is important for the current manuscript to address the uncertainty in HAR in a more substantial way. Referencing the papers is not sufficient in my opinion. Given that so much of the present analyses are based on correlations with convective precipitation in regions that have limited validation, it is important to thoroughly explain what the caveats are and why the precipitation controls describe here are robust despite uncertainty in the data.

AR: Validation and evaluation of HAR: The HAR data set was validated by Maussion et al. (2014) by comparison with rain-gauge observations from the National Climatic Data Center (NCDC) and the satellite derived gridded precipitation data from the Tropical Rainfall Measuring Mission (TRMM). The HAR shows a slightly positive bias in comparison with station data, 0.17 mm/day for HAR10 (0.26 mm/day for TRMM

3B43 product). The comparison with TRMM shows that HAR captures the general features of precipitation seasonality, variability, and spatial distribution. Maussion et al. (2014) found that the HAR10 precipitation averaged over the domain shows 15% more precipitation than TRMM, but these differences are assumed to be related to the well-known underestimation of snowfall and light rain by TRMM. Convective precipitation is simulated in agreement with results from literature, but one has to keep in mind that the model uses a parameterization scheme for cumulus convection. A spatial resolution of 10 km is not high enough to resolve cumulus convection. The HAR is able to reproduce orographic precipitation features as documented by Bookhagen and Burbank (2010). Maussion et al. (2014) state that these qualitative considerations cannot provide a quantitative uncertainty value. Curio et al. (2015) compared the HAR30 atmospheric water transport (AWT) with ERA-Interim. They found similar patterns; the differences being related to the different spatial resolutions and thus a better representation of the underlying topography by the HAR. In the HAR data, the blocking of AWT from the Bay of Bengal by the Himalayas is more pronounced, and the results show the importance of meridionally orientated high mountain valleys for moisture supply to the Tibetan Plateau. For a revised version of the manuscript, we have compared the 300 hPa wind of the HAR with ERA-Interim. Figure R1 shows that they are in a good agreement with each other. Due to the daily reinitialization strategy used to generate the HAR data set, the wind fields in higher levels cannot evolve far away from the forcing data as this is possible for longer model runs. The question how large the uncertainties of the HAR data and especially precipitation are and how we can estimate them, is a topic which should be investigated more in detail. Since there are no other gridded data sets with a comparable high temporal and spatial resolution, the possibilities to validate the HAR are generally limited and will be subject of future research.

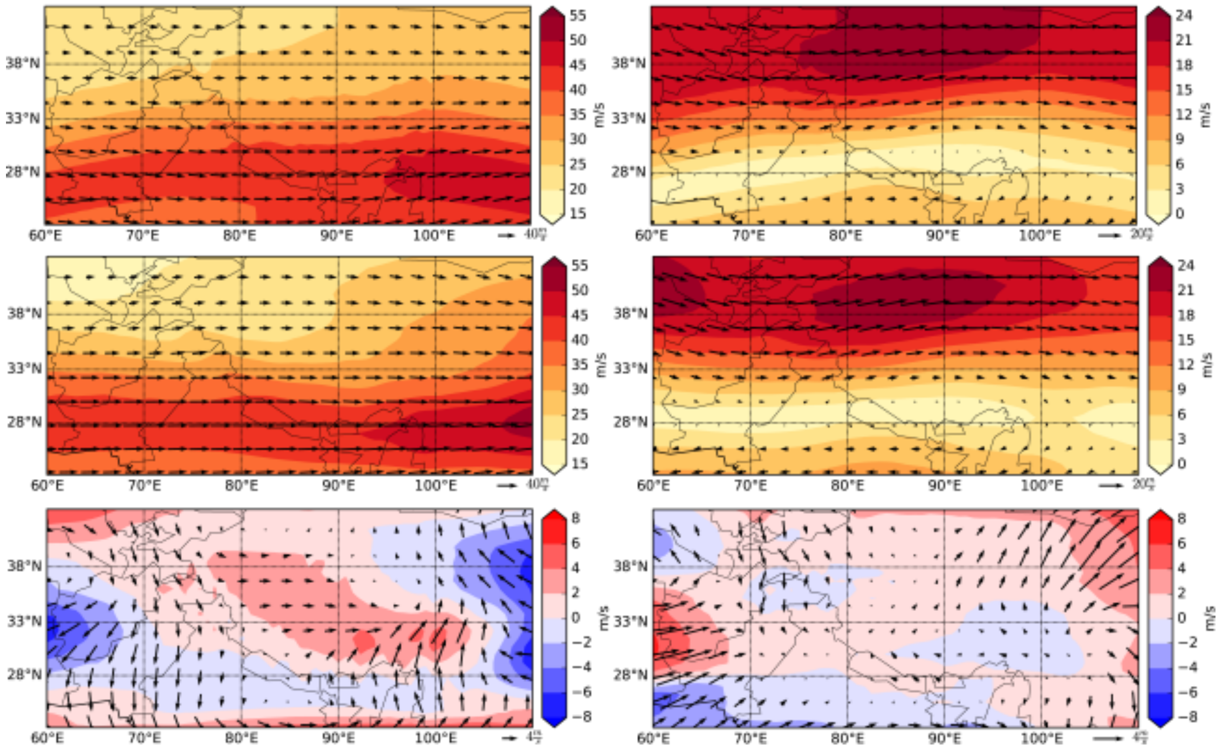


Fig. R1: Mean wind speed at 300 hPa for January (left column) and July (right column) for HAR10 (top) and ERA-Interim (middle) and the differences between them (bottom).

Additionally, we plan to conduct another analysis during the revision of the manuscript to validate the precipitation clusters obtained from the HAR data against NCDC precipitation data. We want to detect whether the stations will occur in the same cluster as the nearest HAR grid points or will be associated to a different cluster regarding their precipitation timing and amount.

R1C2: Moisture variability is not sufficiently investigated in this manuscript. I would like to see atmospheric water vapor treated separately from advection where possible. Because the TP is so high, winds are generally very strong and moisture is minimal. Thus, the water vapor transport variable is much more heavily influenced by wind speed than water vapor. AWT figures in the manuscript confirm this bias by exhibiting heavy influences of the wind speed terms, which seem to mask any water vapor signal (even though they aren't independent). Furthermore, the opposite seasonal cycles of wind and moisture, and their respective sources of variability, may be illustrative of changes in precipitation controls through the year.

AR: We selected the atmospheric water transport and not the column integrated moisture content because this study focuses on dynamic precipitation controls. This means that we focus on dynamical processes that have an influence on precipitation variability and not on the causes of precipitation. Advection of moisture is one of these dynamical processes. The term control means that these variables have a modifying influence on the average precipitation conditions; they can either increase or decrease the precipitation amounts. This shows that there is a covariance between the controls and the precipitation and therefore strong correlations. These correlations are independent from the mean values of precipitation since we use Spearman rank correlation where the correlation is computed using the ranks of the values and not the actual values.

In summer we have high amounts of AWT and the wind speeds are much lower than in winter but we still have high positive correlations with precipitation. We do not think that the correlation figures in the manuscript are in general biased by the wind speed term.

Additionally we calculated the vertically integrated atmospheric moisture content for the HAR and repeated the calculation of correlation for this variable. The result (figure R2) shows high positive correlations between the atmospheric moisture content and precipitation throughout the year, as expected. We plan to add this figure and description to a revised version of the manuscript or to the supplement.

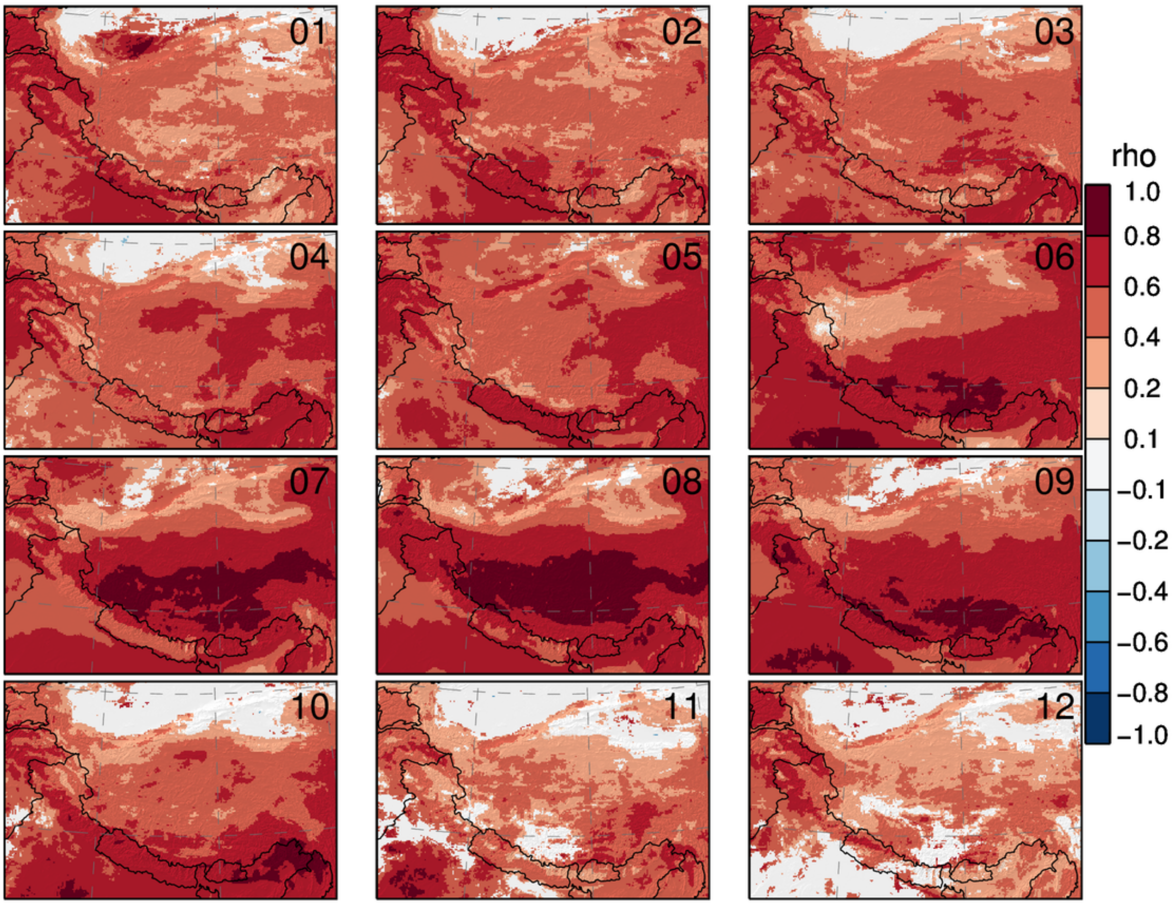


Fig. R2: Coefficient of correlation (rho) between the vertically integrated atmospheric moisture content and precipitation for all months (01-12). Positive correlations are denoted in red, while negative correlations are denoted in blue. Only correlations significant at the 0.05 significance level are shown.

R1C3: The precipitation/pblh relationship over the TP is something that I do not understand well, and would like to see more about, however, this discussion elicits questions about the PBL parameterization that was used in HAR, and it's validity over the TP that can't be answered in this paper. Though Maussion et al. (2011) performed a few PBL sensitivity tests, validation was not done to specifically evaluate PBLH and thus it is impossible to determine how representative this variable is of the actual conditions. Though this is somewhat true for the other precipitation controls used in this study, I am especially skeptical of PBLH because it is not resolved explicitly, and is so poorly represented in other parts of the world. In my opinion, the discussion is an interesting but non-essential part of the paper, and ultimately, I think it is best to remove it.

AR: Thank you for this suggestion which we will follow. In a revised version of the manuscript PBLH will no longer be included. We still find the PBLH a very interesting variable, because it gives information about the turbulent mixing of the lower atmosphere and convection. The PBLH itself is not a pure dynamic variable but entrainment plays a big role and the PBLH is determined dynamically in the HAR data. The PBLH is not the best choice to analyze precipitation controls since it is itself controlled by other variables. Renouncing the analysis of the PBLH helps to keep the manuscript more focused and concise.

R1C4: There are a number of careless grammatical errors and poorly structured sentences in this manuscript that distract the reader. I've noted a few of instances of sentences that were difficult to read in the "technical comments" section, but I encourage the authors to carefully edit the full text.

AR: We will carefully revise the whole text regarding language and grammatical errors. Thank you for highlighting some examples.

Specific Comments –

R1C5: Page 2, Line 10: Why was vertically integrated water vapor transport analyzed and not column integrated water vapor? Since you are already investigating winds, it makes sense to investigate moisture without accounting for wind so that you can determine whether moisture availability is due to advection or local changes in temperature/evaporation? The two aren't completely independent, but they do have opposite seasonal cycles as well as their own sources of variability.

AR: We choose the atmospheric water transport instead of moisture content because we are analyzing dynamic precipitation controls, which have an effect on precipitation variability. They control when and where precipitation is higher or lower in specific regions. Moisture availability is a requirement for precipitation development.

R1C6: Page 2, Line 49-51: Referencing a study of deep tropical convection over the ocean hardly seems relevant to precipitation controls over the TP. It would be better to have a reference for mountain environments, or at least for land areas. If not, it may be necessary to show this relationship using HAR. Furthermore, this sentence is at odds with the negative effect of high horizontal wind speeds on convective precipitation that is described in following sentence.

AR: We agree that the paragraph is not well formulated which leads to the feeling that both sentences are at odds to each other. Horizontal wind speed has different impacts on precipitation depending on the atmospheric level and the type of precipitation. In lower atmospheric levels higher horizontal wind speeds can enhance moisture advection and also evaporation from the land surface. A feedback mechanism between wind, evaporation and convection exists. Higher horizontal wind speeds in higher atmospheric levels, for example the 300 hPa level above the Tibetan Plateau, have a distinct negative effect on convective precipitation by cutting off deep convection and wind shear effects. For a revised version of the manuscript we will revise the paragraph to make clear which effects can take place where and why. We will add references suitable for our study region.

R1C7: Page 3, Line 4: Note that the real benefit occurs because of orographic forcing of the moist flow. Without topography the relationship would be different.

AR: Thank you for this remark, we see that the sentence is not clearly enough formulated. We will revise the sentence and add the importance of the orographic forcing.

Old: “While the positive effect occurs in regions with mainly frontal/cyclonic precipitation because the moisture transport towards these regions is enhanced by the strengthened atmospheric flow.”

New: “The positive effect occurs in regions with mainly frontal/cyclonic or orographic precipitation. Precipitation benefits from enhanced moisture transport by strengthened atmospheric flow, especially when the moisture flow is lifted up by orographic forcing. This plays an important role in our study region because of the high mountain ranges surrounding the Tibetan Plateau.”

R1C8: Page 3, Line 15: It may be interesting to look at atmospheric stability (beyond the PBLH). In convective precipitation, vertical motions occur for different reasons than during frontal precipitation. Looking only at stability (theta or theta-e) would be instructive as to environmental conditions that support vertical motion irrespective of horizontal wind against the orographic barrier. This is important for both summer and winter. (this is only a suggestion)

AR: Thank you for this suggestion, but we think that this goes beyond the scope of the current study. Maybe it would be interesting to include analyses regarding the atmospheric stability in a subsequent study. In this study we focus on the variability of precipitation due to dynamic controls and not on its causes. Since this fact seems not to be clear for the reader we will emphasise the focus of the manuscript.

R1C9: Page 3, Line 41: This raises a number of questions for the reader: Were multiple PBLH schemes tested for WRF? What confidence is there that the PBLH from the configuration with the chosen parameterization is performing well? Were PBLH scheme sensitivity experiments performed in the development of HAR and if so, what observations are they validated with? If PBLH is to be included in this paper (which I’ve already argued against in the general comments section) it is necessary to address these very important questions in the manuscript rather than only providing the reference for HAR.

AR: As already mentioned earlier in the response, we will follow your suggestion, not to include PBLH as a precipitation control in a revised version of the manuscript.

R1C10: Page 4, Line 10: Because this study focuses on convective precipitation, some discussion of the validity of the HAR dataset, which uses a convective parameterization, should be included here. Beyond the reference, the authors should clearly note that precipitation during summer is highly sensitive to the choice of convective parameterization.

Furthermore, they should note that using higher resolutions and resolving precipitation explicitly may alter the spatial and temporal distribution of precipitation. Despite the issues associated with HAR precipitation, I do believe that it is very useful for understanding the mechanisms presented in this paper and the spatial and temporal differences in precipitation across large regions of the TP. I am simply encouraging the authors to further discuss the caveats here so that the reader is aware of these issues.

After all, they may not be familiar with the Maussion articles or may not read them to better understand the data that you have used.

AR: For a general description of the validation and evaluation of the HAR data please our response to reviewer comment R1C1. Of course using different parameterizations and higher spatial resolutions would change the precipitation values and its spatial and temporal distributions. But we assume that this would not change the the main results of this study since we use rank correlations which are independent of the mean values and scaling of the variables used in the correlations.

R1C11: Page 4, Line 32-33: I am curious as to how many days are included in the precipitation analysis. It seems that a threshold of 0.1 in the Karakoram and western Himalaya would remove very few days from consideration through the winter months. Why was a percentile-based threshold not used in addition to this low threshold to further exclude days with light precipitation that don't really contribute to seasonal totals in an area such as the KH. Including these dates masks the signal of precipitation controls during events that contribute strongly to overall precipitation accumulation (e.g. in the Karakoram and western Himalaya only a few dates during the winter season contribute the majority of seasonal (and in some cases, annual) precipitation).

AR: The threshold was basically used to filter out numerical artefacts in the data and not to exclude specific events from the data base. Since the precipitation distribution on Tibetan Plateau and surrounding high mountain ranges is very diverse, we do not want to exclude light precipitation events, because in some regions they can play a greater role for seasonal or annual precipitation than in the western Himalaya region. We decided to use a threshold that is able to filter out numerical artefacts but does not further reduce the number of precipitation days. We do not want to examine control mechanisms only for selected events. Maybe, we could examine whether the effect of selected dynamic variables on precipitation is different for extreme/intense precipitation events, in a subsequent study.

R1C12: Page 4 Line, 43-44: Do correlations in regions of sparse precipitation exhibit considerable sensitivity to a few extreme events? If you threshold out the largest few events (99th percentile) would the correlations change?

AR: I assume that if we would mask out the largest few events we would not have enough data for a reasonable correlation analysis. One of the conditions for a grid point to be considered for further analysis is a number of at least 13 precipitation days during all days of one month during the study period (2001-2013). Since the rank correlation is based on the ranks of the data and not on the values itself a few extreme events would just slightly change the results.

R1C13: Page 5, Line 20-22: The yellow and green classes may be very sensitive to the cumulus parameterization scheme that was used in HAR. Due to the uncertainty in how well WRF, and specifically HAR in this case, represent convective precipitation in the Himalaya, I don't think these classes can be so clearly defined. At the very least, better discussion of the caveats must be given, but it may be better to not distinguish these groups since the precipitation controls discussion does not.

AR: You are right that due to the use of a convective parameterization scheme uncertainties regarding the convective precipitation exist. But we think that there are still differences in the impact of the monsoon system on these classes. We think it is an interesting result that these regions exhibit two different cluster. We explain in the text that it is not possible to draw a sharp border between the classes but that their existence can give a hint to the extent of the influence of the Indian summer monsoon on the precipitation on the Tibetan Plateau, a topic that is widely discussed in literature. Apart from choosing the number of clusters the cluster analysis itself is a quantitative and objective method. Since other numbers of clusters lead to similar results, the differentiation between these two clusters (yellow and green) is not an artefact. The results for varying the number of clusters are displayed in figure 5 in the response to reviewer comment R3C10.

R1C14: Page 6, Line 1: It seems to me that the reason the high elevations of the eastern Himalaya (near the Brahmaputra Channel) exhibit considerable precipitation contributions outside of the monsoon season is due to the orographic locking of westerly flow and the large amount of available moisture in this area. See Norris et al. (2015; their Figs. 5&6), which are focused on westerly disturbances affecting other regions of the Himalaya, but in both cases, exhibit precipitation in the eastern Himalaya generated by terrain locking of westerly flow.

AR: Thank you very much for this remark and the literature suggestion. We will consider this during the revision of the manuscript.

R1C15: Page 6, Line 30-32: This should cite some of the more seminal work on westerly disturbances.

AR: Please see our response to next comment.

R1C16: Page 6, Line 32-33: Higher wind speed does not necessarily mean enhanced moisture supply. There are many factors that modulate both wind and moisture in these systems (see Cannon et al. 2015). I would suggest just removing “which benefits from enhanced moisture due to higher wind speeds” and stating that the cyclonic/frontal precipitation is associated with westerly disturbances and then add a citation (e.g. Dimri et al. 2015 – review paper of westerly disturbances).

AR: Thank you very much for the literature suggestions. We will add some citations on westerly disturbances and a short description on the occurrence of westerly disturbances and their role for precipitation in the western part of our study region.

R1C17: Page 7, Line 2: Figure 1 indicates that the western Himalaya receives more than 0-5% of annual precipitation during summer (June alone is over 5% for Cluster 0). Furthermore, some studies argue that about 30%-60% of precipitation in this region falls during summer (e.g. Bookhagen and Burbank, 2010; their Fig. 4). Though the Bookhagen and Burbank estimate is probably too high because it is based on TRMM, which doesn’t do well with winter precipitation, it is clear that considerable rainfall occurs in the western Himalaya during summer. Given that there is precipitation, what then could explain the lack of correlation?

The results show high positive correlations of precipitation with AWT in lower levels. The western disturbances which are responsible for the main part of precipitation in the western part of the study region occur primarily in winter. We assume that in summer the heating of the slopes in the western Himalayas leads to convection.

Therefore, moisture advection in lower levels seems to be more important than strong westerly winds at 300 hPa which act as a path way for westerly disturbances to the study region in winter. Our results are in good agreement with the precipitation amounts stated by Bookhagen and Burbank (2010). Cluster 0 receives ~35 % during May to October, while Cluster 5 receives ~60 % during the same time. The statement in the manuscript that there is almost no precipitation in the Pamir Karakoram region in summer is an error caused by changing the sentence from talking about July to the entire summer season without changing the values. We apologize for this error and for causing confusion. We will correct this in the revised manuscript. The value of 0-5% refers to Fig. 9 in Maussion et al. (2014) which shows the contribution of every month to the annual precipitation.

R1C18: Page 7, Line 7-8: Remove the linkage between higher wind speed and enhanced moisture. I would argue that higher wind speed more efficiently extracts moisture due to stronger orographic forcing. As mentioned before, there are many controls on moisture availability in the western Himalaya that are independent of the cross-barrier wind speed.

AR: The focus of the study is to analyse the effect of dynamic variables on the variability of precipitation and the mechanisms through which these controls can lead to an increase or decrease of precipitation. The variability of precipitation is determined by different controls according to different regions and seasons. Our results show that the atmospheric water transport and the wind speed in 300 hPa have different impacts on precipitation variability in different regions and seasons. Of course moisture availability is a limiting factor for precipitation development, but the causes of precipitation are not topic of this study. Since it seems that this was not clearly enough stated in the manuscript we will revise the manuscript to make this clear.

R1C19: Page 7, Line 32-39: The alternating positive/negative correlations look more like a gravity wave (i.e. updrafts and heavy precipitation on windward side of the mountain, downdrafts and light precipitation in the lee; Roe et al. 2005) than an error associated with aggregation. There should be an easy way to show this using topography aspect and wind direction, or using higher temporal resolution data available from HAR.

AR: We also think that it is a physically correct pattern, we just wanted to make the reader aware that we cannot exclude aggregation induced errors. Please see our response to reviewer comment R1C23. Although our study is quite extensive we cannot answer all questions exhaustively. We do not want to examine these questions more in detail here because they will be subject of upcoming research using the HAR data.

R1C20: Page 7, Line 41: I recommend looking at the correlation of precipitation and precipitable water rather than precipitation and water transport (or at least in addition to it). This is particularly important to do since convective precipitation requires enhanced moisture content, but not enhanced wind, while orographic precipitation requires both enhanced wind and enhanced moisture. Even though wind and moisture aren’t independent, it would be interesting to see a figure of just the precipitable water correlations since it does not include the advection term, for which a similar variable was shown in previous figures (WS300, WS10). This could be particularly illustrative since the seasonal cycles of moisture availability and wind speed are opposite for this region (e.g. Cannon et al. 2015).

AR: We will repeat the analysis for an additional variable representing the moisture content in the atmospheric column. Since we want to focus on dynamic precipitation controls we do not want to exclude the atmospheric water transport.

R1C21: Page 8, Line 31: I don't see the need to introduce boundary layer height, which is controlled by other processes that have already been evaluated. I don't think this adds much to the discussion, which was already quite strong. Furthermore, PBLH is parameterized in WRF, so you're introducing another question about how well this parameterization works, rather than focusing on variables that are explicitly resolved (moisture, temperature, wind). Though Maussion et al. 2011 performed a few sensitivity tests with different PBL parameterizations, validation specific to PBLH using radiosondes or wind profilers over the TP has never been done, so there are a lot of unknowns here. The lakes discussion is certainly interesting, but given the uncertainties about WRF's ability to resolve these processes, and because this discussion is not a main topic in the paper, I suggest leaving it out.

AR: We will follow your suggestion and will no longer include the PBLH analysis in a revised version of the manuscript. We still find the PBLH a very interesting variable, but think that your concerns are right. Since the PBLH is itself controlled by other variables it is probably not the best choice to analyze precipitation controls.

R1C22: Page 11, Line 33: The uncertainties in HAR should include the use of a convective parameterization, which directly affects the precipitation data (presence, timing and magnitude) that this study is based on. A better description of this particular issue is required since it is possible that some of the results in this work are sensitive to the choice of parameterization (or that if HAR were performed to explicitly resolve convection (<6km)).

AR: We will add a sentence about the use of a convective parameterization scheme and the related uncertainties to the section where we will discuss the validation/evaluation and uncertainties of the HAR. Please see our response to reviewer comment R1C1.

R1C23: Page 11, Line 48: Did you try using hourly or 3-hourly data to test what role aggregation errors play in your research? It seems that you have the necessary data to directly address this uncertainty.

AR: We also think that it is a physically correct pattern, we just wanted to make the reader aware that we cannot exclude aggregation induced errors. Maybe this remark was misleading the reader, so we will better explain our thoughts about the causes of this pattern. If an air flow hits a mountain range, the barrier causes orographic induced flow patterns, with updrafts on the windward side and downdraft on the lee side of the mountain range. This causes the precipitation to be smaller on average on the lee side because the downdrafts supress precipitation development. In the case of stronger flow to the mountains we also get stronger moisture advection and therefore the downdrafts are no longer able to supress precipitation. This leads to the simultaneous occurrence of precipitation and downdrafts which is the reason for the negative correlation patterns on the lee side of mountain ranges found in this study. To figure out the role of aggregation errors goes far beyond the scope of this study. There are plans for future studies where the meteorological processes will be analysed explicitly using the available higher temporal resolutions. An aim of subsequent studies will be to assess the uncertainties of the dataset using, for example, newly available satellite data.

Technical Comments –

R1C24: Page 1, Line 7-8: Change “moisture” to “water resources”

AR: OK

R1C25: Page 1, Line 32: Change “strengthen” to “strengthening”

AR: OK

R1C26: Page 2, Line 1-8: A few of these sentences were difficult to read. A little restructuring would help the reader here.

AR: We will restructure these sentences in a revised version of the manuscript.

R1C27: Page 2, Line 25: When introducing the acronyms (PBLH, AWT and WS300), they should first appear next to their full names.

AR: OK

R1C28: Page 3, Line 7 & 18: “luv side” should be changed to “windward” as that is the common terminology in meteorology textbooks. (change in all instances)

AR: OK, thank you for this suggestion.

R1C29: Page 4, Line 24-25: Did you aggregate daily, or are you using a specific time-slice for each day?

AR: We aggregate the hourly model output to daily data. We use all time steps available for a day and not a specific time slice.

R1C30: Page 5, Line 21: Change “intensive” to “pronounced”. Intensive makes it sound as though this relates to magnitude of precipitation values rather than the shape of the distribution.

AR: OK, done.

R1C31: Page 6, Line 13-14: remove “and therefore exhibit no coherent patterns”. The patterns are coherent when considering mesoscale, synoptic and large-scale influences as well as topography. The patterns are complex and heterogeneous, but not incoherent.

AR: OK, thank you.

R1C32: Figure 2: The cyan and yellow lines are difficult to see. Perhaps all the lines could be thicker or darker colors could be used

AR: For a revised version of the manuscript we will also revise this figure to make it easier to read.

R1C33: Page 7, Line 12: “There are high positive correlations (over the Tibetan Plateau?) between WS10 and precipitation. . .”

AR: Yes. We will add the region to the sentence.

R1C34: There are too many small mistakes in word choice, grammar and sentence structure to identify each individually. I encourage the authors to carefully edit the full text.

AR: We will carefully revise the manuscript regarding word choice, grammar, and sentence structure.

Anonymous Referee #2

Received and published: 21 March 2016

This manuscript analyzed the seasonality and spatial variability of dynamic precipitation controls on the Tibetan Plateau using HAR dataset. It stresses the high impact of the mid-latitude westerlies on precipitation distribution on the TP and its surrounding year-round. I can feel the strong eagerness of authors on concluding the westerly is the controller of the precipitation over the TP. However, manuscript is supportive enough. I have great concerns before the conclusions could be drawn. Substantial revisions are necessary before the manuscript is publishable.

R2C1: All of this work is based on the single approach – correlation and single data set – HAR. Large uncertainties in conclusions occur due to the approach adapted and data set used. Multiple approaches or datasets are necessary to swipe away these uncertainties.

AR: The HAR data set is physically based and also forced with a physically based data set. The comparison with ERA-Interim and the validation with TRMM and station data show that the HAR is suitable to analyse precipitation variability. It is true that we cannot remove all uncertainties. But since the HAR data set is the only dataset with such a high spatial and temporal resolution available for the entire Tibetan Plateau and surrounding high mountain ranges we do not have a real opportunity to use multiple datasets. We will add a section about the uncertainties of the HAR data and describe the validation and evaluation done for the data so far.

R2C2: More validation and evaluation on HAR are of fundamental necessity before it could be used on analyzing.

AR: Please see our response to reviewer comment R1C1. In a revised version of the manuscript we will add a paragraph about the validation and evaluation of the HAR data and the resulting uncertainties.

R2C3: The whole basement of this study is the precipitation classification by Maussion et al. (2014). However, the precipitation classification Maussion et al (2014) did is for only the glacier accumulation regimes locating at high altitudes above about 5000m shown in their Fig. 14, rather than for the whole Tibetan. Is it representative for the precipitation over the whole TP? If so, please show the evidences. If not, suggest changing the title to ". . .on the glacier accumulation regimes over the Tibetan Plateau"

AR: The precipitation classification in this study is based on the idea to use a clustering method to determine accumulation/precipitation regimes for glacier regions done by Maussion et al. (2014). We conducted a cluster analysis for the entire Tibetan Plateau and surrounding high mountain ranges using the HAR data, which should be clear if looking at figure 2. Since this seems not to be clear we will revise this section. Since we do not focus on specific areas, e.g. glacier areas, our precipitation classification is based on a larger data set and provides more information.

R2C4: P2L47, it reads "on average, more than 60% of moisture needed for precipitation falling on the inner TP are provided by the TP itself (Curio et al. 2015)". In authors' previous paper published in 2015. That suggests that convections over the TP dominate precipitation in the TP rather than the moisture transportation from outside. In this manuscript, the westerly are argued to be the dominant controller in precipitation. These two conclusions are conflict to each other. Which one is the leading controller of the precipitation in the TP, in authors' ultimate view? What is the linkage of the convections and the westerly? Considerate analysis and evaluation are strongly suggested before the conclusion is drawn.

AR: We do not think that these two findings are conflict to each other. The moisture recycling is the dominant feature regarding the question where the moisture for precipitation on the TP is coming from, while the dynamic precipitation controls related to the subtropical jet (wind speed at the 300 hPa level and the atmospheric water transport) are found to be dominant regarding the variability of the precipitation. One is the provider of necessary moisture while the others are dynamic effects which control precipitation variability. The subtropical jet causes a decrease of precipitation in regions which are dominated by convective precipitation while it causes an increase of precipitation in regions which are dominated by frontal/orographic precipitation.

R2C5: Over ocean or area with low elevations, 300 hPa is high enough to stand for the height that the westerly locates. However, the TP possesses an elevation above 4000m on average. 300 hPa is too low for the westerly over there. Authors cite Schiemann et al. (2009) as the reason of this selection. We can read the cited reference is about the precipitation climate of Central Asia. The TP possesses distinguish climate from the Central Asia not only in its unique height, but also the distance from the ocean. They are not comparable. Authors should refer to works in the TP rather than other where. Numerous studies claim that the westerly reaches as high as 100 hPa over the TP. For instance, 200 hPa (in the global climate model domain, Gao et al., J. Climate 2014) or 100 hPa (in regional climate model domain, Gao et al., J. Climate 2015) are the height where the westerly hang over the Tibetan; whereas, the 600 hPa (in the global climate model domain) or 500hPa (in regional climate model domain) is the near surface. The 300 hPa is a middle layer between the upper and near surface layers. It is reasonable using the vertical wind speed at 300 hPa for the vertical motions. However, the horizontal wind speed at 300 hPa used to represent the westerly jet over the Tibetan is questionable.

AR: We decided to use the wind speed at the 300 hPa level because the wind shear in this height more strongly suppresses deep convection than at the 200 hPa level where the core of the jet lays. Also we assumed that the results would not change overall using the wind speed in 200 hPa. To proof that, we repeated the correlation analysis between wind speed and precipitation for the wind speed in 200 hPa (figure R3). The results are very similar. The correlations at the 300 hPa level (figure R4) are slightly higher because the negative effect of higher wind speeds on precipitation by cutting off deep convection is higher at this level than in 200 hPa. We will add this analysis to the supplement of the revised manuscript.

Another supporting reasons is the finding by Mölg et al. (2014) that the flow strength at the 300 hPa level has a strong influence on precipitation in the regions influenced by the monsoon. Furthermore, the westerly jet reaches nearly down to the surface over the Tibetan Plateau and the 300hPa level lays still within the band of westerly winds with higher wind speeds associated with the jet stream as shown by Maussion et al. (2014) in their figure 2.

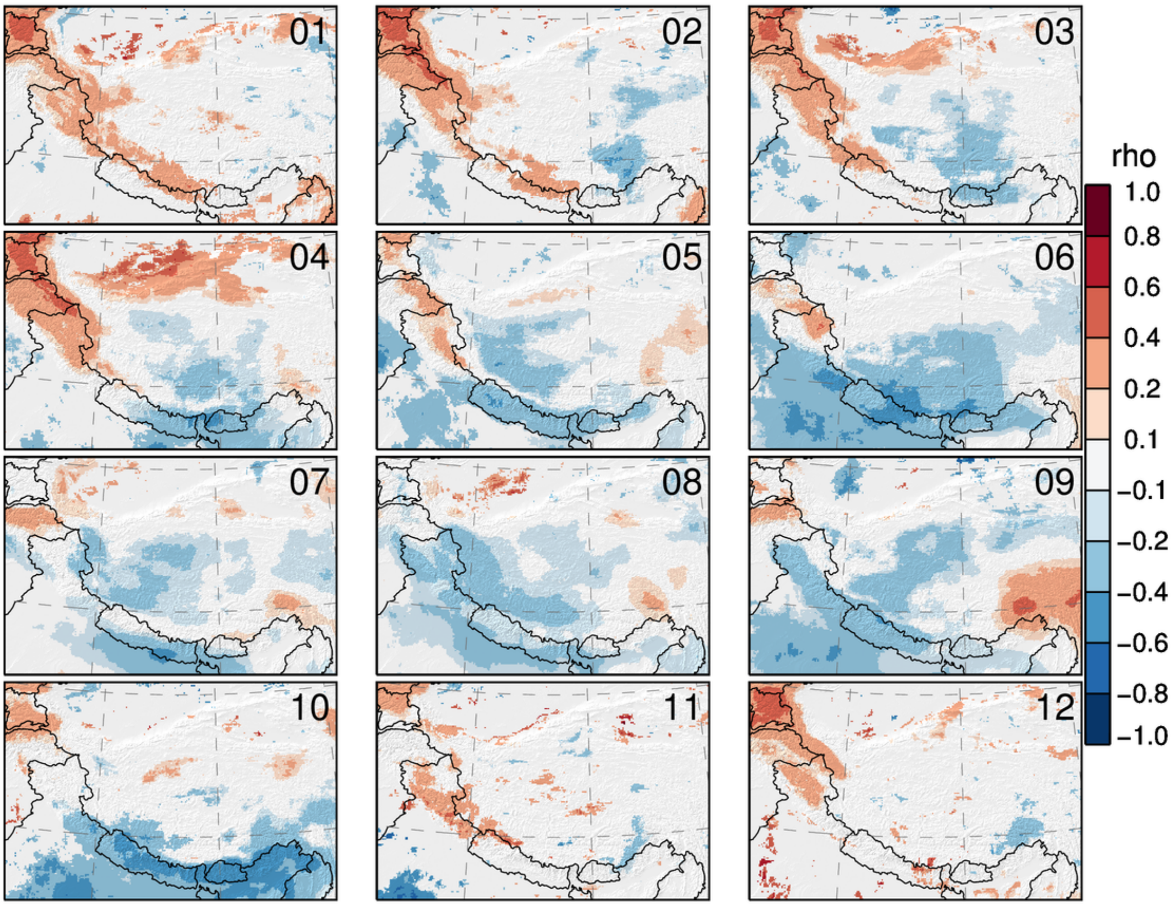


Fig. R3: Coefficient of correlation (rho) between the horizontal wind speed at 200 hPa and precipitation for all months (01-12). Positive correlations are denoted in red, while negative correlations are denoted in blue. Only correlations significant at the 0.05 significance level are shown.

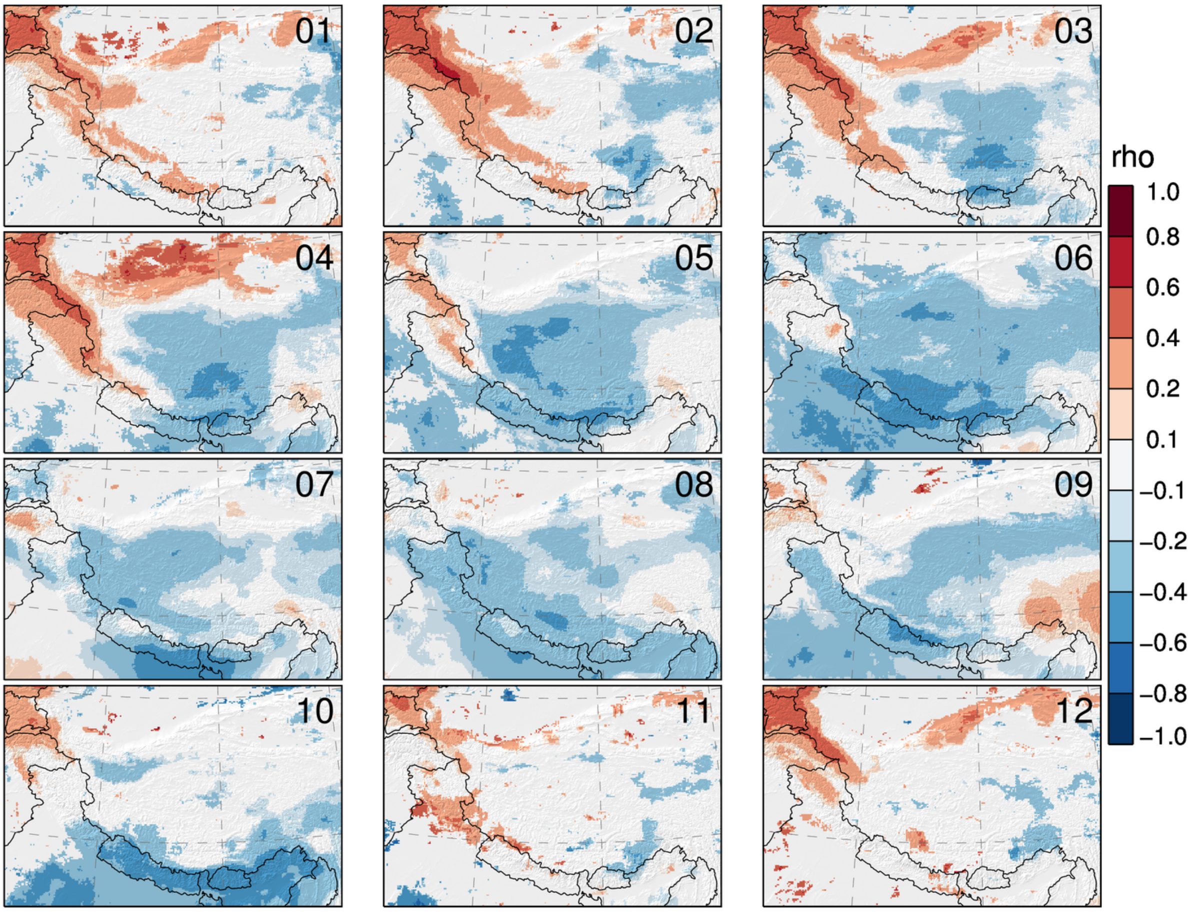


Fig. R4: Coefficient of correlation (rho) between the horizontal wind speed at 300 hPa and precipitation for all months (01-12). Positive correlations are denoted in red, while negative correlations are denoted in blue. Only correlations significant at the 0.05 significance level are shown (originally figure S3 of the supplement).

R2C6: It is claimed that “Six controllers are selected”. However, five are analyzed in 3.2.1a, 3.2.1b, 3.2.2, 3.2.3 and 3.2.4. Do I missing something? Before the controller is concluded, I prefer to call them elements rather than controller. In addition, background of these elements is missing. Why these elements are chosen? What is their relevance with precipitation? For instance, the horizontal wind speed at model level 10 (WS10) is used. What is the height of model level 10? What it stands for? Is the PBLH relevant to PBL parameterization schemes used in simulation?

AR: You are right that we only describe five precipitation controls in the section about the correlations with precipitation. We left out the vertical wind speed at model level 10, because we did not want to repeat things which are quite similar to each other. In a revised version of the manuscript we will remove the analysis of the vertical wind speed at model level 10. Since we will also no longer use PBLH as a precipitation control (due to reviewer suggestions) we will only analyse four variables as precipitation controls in the revised version of the manuscript.

The height of model level 10 is about 2 km above ground over the Tibetan Plateau. We chose this level to represent processes taking place within the boundary layer, which can exceed 3 to 4 km above ground over the Tibetan Plateau. It is located in the middle to upper range of the planetary boundary layer.

We will consider the use of the term “elements” instead of “controls”. But maybe we can keep the term controls if we better explain that precipitation controls do not necessarily control whether precipitation occurs or not, but rather (control) the spatial and temporal variability of precipitation.

We describe each element in the introduction and their relevance for precipitation. Since it seems not to be clear enough we will revise this section. We made the mistake not to state clearly enough that the selected elements control the precipitation variability. We just named precipitation development which leads the reader to the wrong assumption that we claim that there would be no rain without the influence of the dynamic precipitation controls. To make this clear will be part of the revision of the manuscript.

Anonymous Referee #3

Received and published: 21 March 2016

Summary:

The study described in this manuscript investigates the impact of five selected dynamic controls (horizontal wind speeds at different levels, vertical wind speed, atmospheric water transport and planetary boundary layer height) for precipitation in High Asia. The study’s novelty lies in the use of a relatively new high resolution dataset to answer questions that have previously not been addressed. The conclusions reached are supported by the findings. They are scientifically valuable and presented in a logical and intuitive way. The title and abstract are concise. However, I do have a few questions, concerns and suggestions regarding the methods applied and language used in the manuscript. After consideration of those and moderate revisions I recommend publication of this manuscript.

General Comments:

R3C1: The statistical methods used in this study are suitable for addressing the questions. However, since the findings and conclusions rely heavily on purely statistical methods (mostly Spearman’s rank correlation), I would like to see them discussed in more detail (see specific comments). The authors should also describe how the significance of rho was calculated. (I believe this is missing entirely from the manuscript). The PCA is suitable for describing the spatio-temporal variability of correlation of controlling factors and precipitation.

AR: Please see response to comment R3C8 for a detailed description of the statistical method and the calculation of the significance.

R3C2: I am not sufficiently familiar with specific shortcomings of the HAR dataset to comment on whether or not the authors adequately addressed these in the manuscript and took them into consideration when drawing conclusions. However, since this study is entirely based on HAR, I would appreciate some comments on existing uncertainties of the dataset and how/whether or not this limits the interpretation of the results of this study.

AR: Please the response to comment R1C1 regarding the same topic.

R3C3: There are numerous grammatical errors throughout the manuscript and sentence structure is often confusing. This makes it very difficult to read and understand in certain sections. I highlighted some of these in the “technical comments” below. I strongly recommend the authors edit the language of the manuscript and let a native speaker (or someone with a similar level of written English) review it before resubmission.

AR: Thank you for this remark and recommendation. We will carefully revise the manuscript, remove grammatical errors and improve the sentence structure.

Specific Comments:

R3C4: Page 2, line 8: You write here and later on that you select six factors. However, you only list five here (and in the results). Maybe I am missing something?

AR: You are right that we only describe five precipitation controls in the section about the correlations with precipitation. We left out the vertical wind speed at model level 10, because we did not want to repeat things which are quite similar to each other. In a revised version of the manuscript we will show and discuss the figures and the differences to the correlations of the wind speed in 300 hPa and precipitation.

R3C5: Page 2, line 15: What is this assumption based on? I expected a little more explanation for the selection of controlling factors – scientific or purely technical. Also, what factors were excluded and why?

AR: Since the precipitation distribution on the Tibetan Plateau is influenced by both the Indian Summer Monsoon and the mid-latitude westerlies (e.g. Maussion et al., 2014; Böhner et al., 2006), we focus on dynamic precipitation controls which are related to these two atmospheric circulation features. We have to make more clear that the focus of the study is not to examine precipitation development but the reasons for precipitation variability. We apologize that the former use of the phrase precipitation development was misleading the reader. This variability is influenced by the atmospheric circulation and the related variables like horizontal and vertical wind and moisture transport. We choose variables from the HAR data set, which are already proven to be in good agreement with observations and gridded datasets. The selected controls are well known to have an impact on precipitation variability. The positive effect of AWT on precipitation variability is described in, for example, Barros et al. (2006), Giovannetone et al. (2009) and Zhou et al. (2005). The positive effect of higher wind speeds on moisture advection and orographic lifting, and in lower levels enhancing evaporation and therefore their positive correlations with precipitation are known in the literature (e.g. Johansson and Chen (2003), McVicar (2012), Roe (2005)). Higher wind speeds in higher atmospheric levels can cut of deep convection via the wind shear effect, studies showing this effect are, for example, Findell et al. (2003) and Zhang and Atkinson (1995). Rose et al. (2003) show effects of vertical wind speed and most important its direction on precipitation. Updrafts lead to an increase of precipitation while downdrafts lead to a decrease of precipitation. Of course there are other variables influencing precipitation, but we think that our selection is suitable for our study region. We will add some of the references to the introduction of the revised manuscript to support our selection of variables.

R3C6: Page 4, line 33: How was the 0.1mm threshold chosen? In context of the study's aims, what are the advantages of choosing an absolute value instead of a grid-box specific percentile for example?

AR: The threshold was basically used to filter out numerical artefacts in the data and not to exclude specific events from the data base. The threshold of 0.1 mm per day is also a commonly used minimum value to define a precipitation day (e.g. Martin-Vide, J., & Gomez, L. (1999), Ceballos et al. (2004), Polade et al. (2014), Lana et al. (2006), Liu et al. (2011), Bartholy et al. (2010), Frei et al. (1998)).

R3C7: Page 4, line 37: It may be more insightful to highlight the advantages of the Spearman rank correlation over other measures of statistical dependence for this particular question involving precipitation and its controlling factors.

AR: We will add a description of the statistical methods in the revised version of the manuscript. The Spearman rank correlation was chosen because this measure is more robust against outliers in the data. Since the spatial and temporal distribution of precipitation is very different in specific region on the Tibetan Plateau the range of values is very large. The rank correlation also can help to reduce the effect of very intense or very light rain events on the correlation results.

R3C8: Page 4, line 39: There are multiple ways in which the statistical significance of such a correlation can be determined. I recommend that you at least mention in one or two concise sentences how it was determined in this study. Also, how sensitive are your results to different, commonly used significance levels, e.g. 0.01? Since the correlation analyses form the centre piece of your study (and the PCA's are also based on correlation coefficients), I think it is necessary to provide a little more insight.

AR: The statistical significance of the results was tested using a two tailed test to determine the deviation from zero. We used the r_correlate routine of the software IDL to compute the Spearman rank correlation and its level of significance. The source code references to the textbook "Numerical Recipes, The Art of Scientific Computing (Second Edition), Cambridge University Press, ISBN 0-521-43108-5". The pages 640-642 describe the Spearman Rank-Order Correlation Coefficient. The two-sided significance level is extracted from the t-value based on the degree of freedom (N-2) and its beta distribution. The routine returns the variable probrs, which is the p-value and gives the significance of the correlation coefficient. A small value of probrs indicates a significant correlation. This value has to be compared with the value set for the significance level in order to determine whether it is significant at the given significance level or not.

rs: Spearman rank-order correlation coefficient

N-2: degrees of freedom

```
t = rs * sqrt(N-2 / 1-rs2)                               ;its t-value

probrs = betai(0.5 * (N-2), 0.5, (N-2) / (N-2) + t * t)   ;its significance, p-value
```

To test, how sensitive the results are regarding the use of a different significance levels, we repeated the analysis with the significance level 0.01 for the correlation between wind speed in 300 hPa and precipitation (figure R5) and compared the results with the results gained using 0.05 as significance level (figure R6). The resulting patterns do not change very much. The areas with negative and positive correlations are a little bit smaller, but the changes occur where the values are already lower (at the borders of the correlation patterns). The regions with the highest correlations stay stable and even small areas of positive or negative correlations do not disappear.

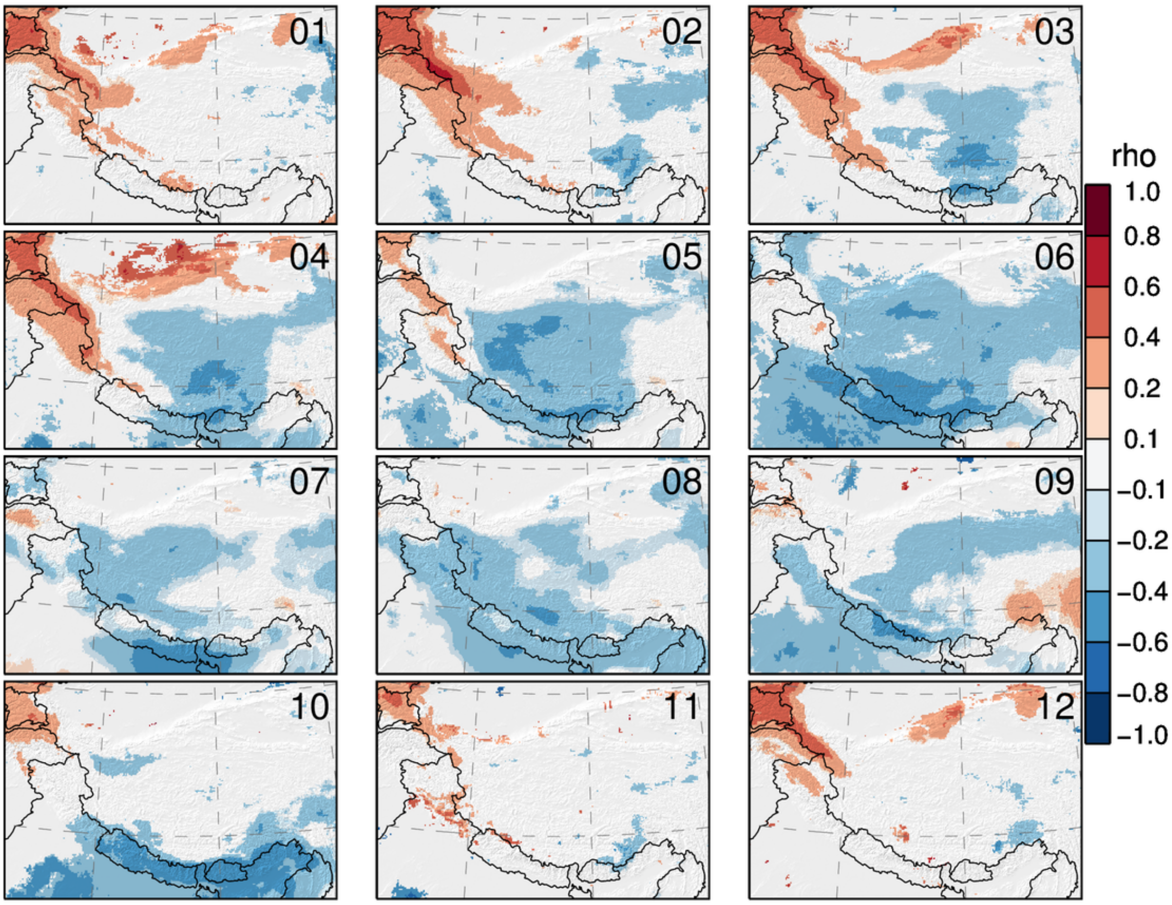


Fig. R5: Coefficient of correlation (rho) between the horizontal wind speed at 300 hPa and precipitation for all months (01-12). Positive correlations are denoted in red, while negative correlations are denoted in blue. Only correlations significant at the 0.01 significance level are shown.

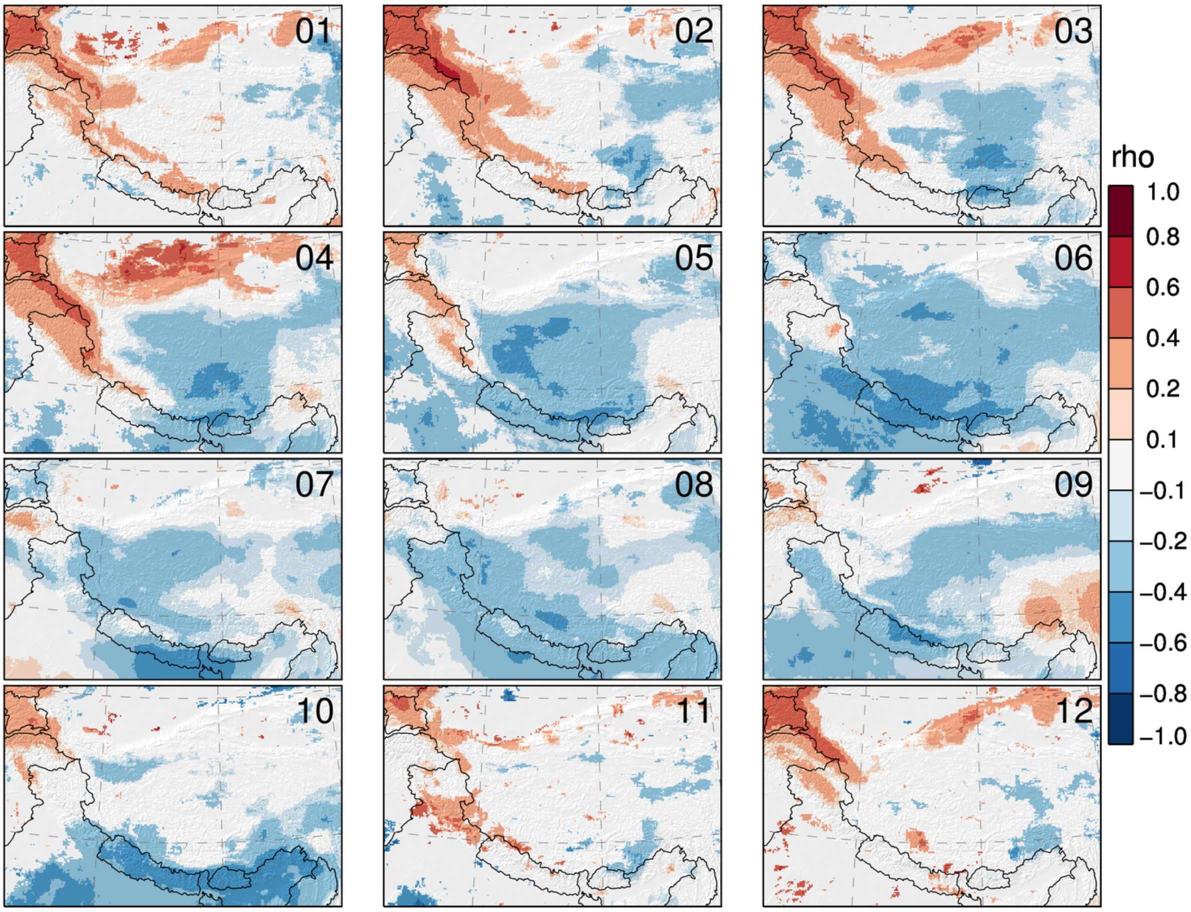


Fig. R6: Same as Fig. R5, but only correlations significant at the 0.05 significance level ar shown (originally figure S3 of the supplement).

R3C9: Page 5, line 1-3: Maussion et al. use this clustering approach to classify glacier accumulation regimes. While the analysis itself is a universal tool of of descriptive statistics fitting for the aims of the study, I recommend the addition of justification for deviation from the Maussion et al. clustering since you present this as something that builds on that study. For example, why choose seven instead of five clusters as Maussion et al. do? (see comment below)

AR: Please see response on next comment.

R3C10: Page 5, line 5-8: As I understand, you varied k for the clustering to determined the optimal number, i.e. the number giving you good coherence within the classes and sufficient distinctions between them. What was the k range you used and how did you determine optimal k? Was this apparent from a qualitative assessment of plotted results or was it determined by something like a discriminant analysis? Furthermore, for similar clusters such as purple/red and yellow/green, I recommend adding comments on the sensitivity of the clustering to physical conditions versus HAR/WRF limitations. In other words: is the separation of yellow and green physically meaningful?

AR: We varied the k for clustering from 5 to 9, we choose to start with 5 because this was the k used in the Maussion et al. (2014) study for glacier regions. We found 7 to be the optimal k for the recent study since it gave us good coherence within the classes and sufficient distinctions between them, like you say and we state in the manuscript. We determined this qualitatively by looking at the plots for the different numbers of clusters. We first conducted the cluster analysis with 5 clusters like Maussion et al. (2014). But since we included a much higher number of grid points (we analysed the entire Tibetan Plateau), the results for the areas included in both analyses look slightly different especially in the Karakoram and Tien Shan. By increasing the number of cluster to 6, one cluster that covers most parts of the northern part of the study region, northern Tibetan Plateau and Tarim Basin, breaks up in two cluster. Setting the number to 7, we get more variation in the Karakoram and Tien Shan which looks more similar to the cluster distribution achieved by Maussion et al. (2014). Using a higher number of clusters led to the occurrence of more clusters of smaller size which are not as distinct from each other as the larger ones. In general, it would be interesting to have more cluster to get a higher spatial differentiation. But by increasing the cluster number the spatial coherence decreases and therefore the interpretability also decreases. We decided to use seven clusters as a compromise between higher spatial differentiation and less spatial coherence. If requested, we can add the plots for the different cluster numbers to the supplement of the manuscript to give the reader the chance to get an idea of the differences. Since the core areas of the clusters stay stable while changing the number of clusters we do not think that the clusters are an artefact. The results for the different cluster numbers are shown in figure R7.

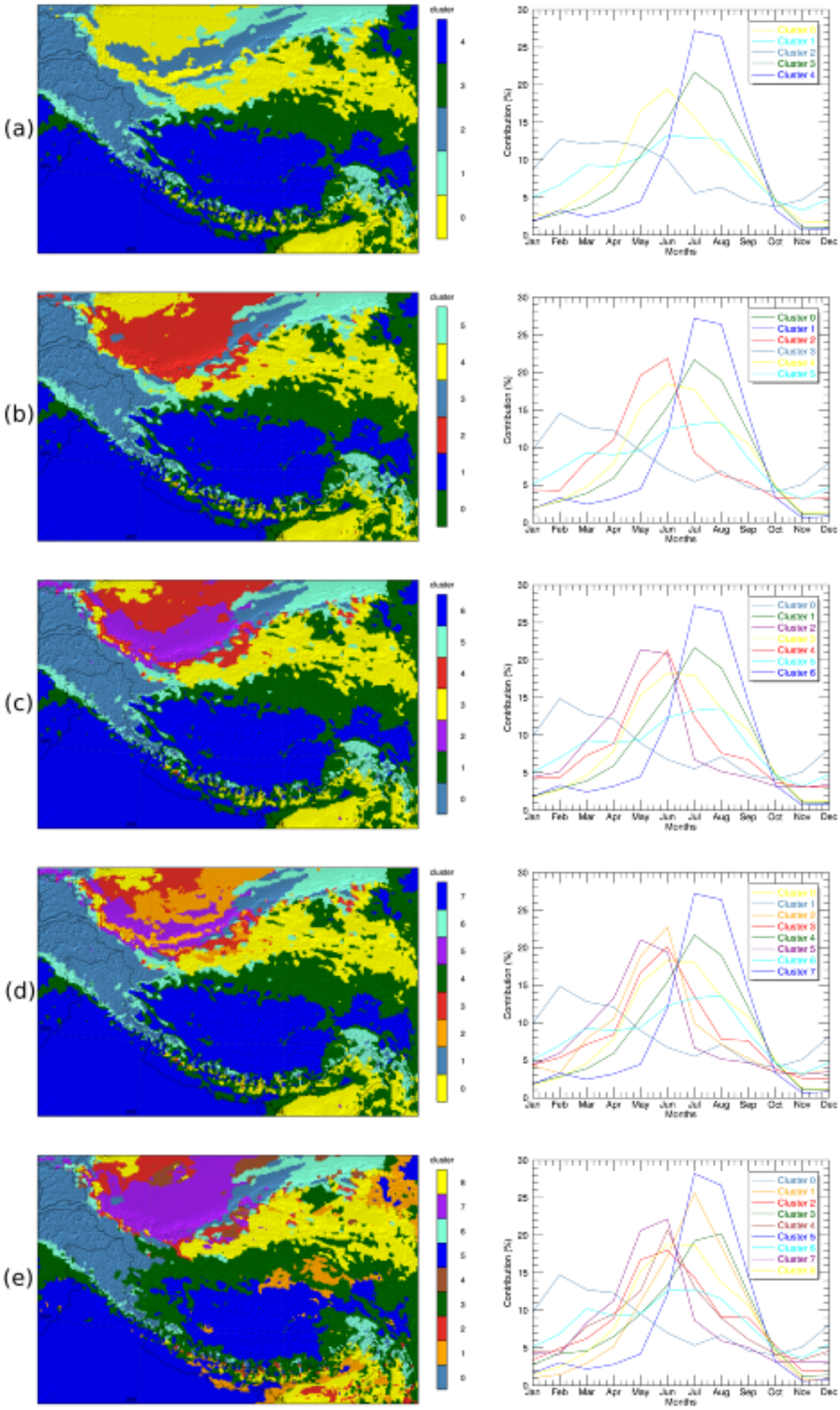


Fig. R7: Precipitation cluster (left) and the mean annual cycle of percentage contribution of monthly precipitation to annual precipitation for each cluster (right) for different numbers of clusters: 5 (a), 6 (b), 7 (c), 8 (d), 9 (e).

R3C11: Page 7, line 32: Could this pattern be the result of a gravity wave?

AR: Thank you very much for this remark. It is possible that this pattern could be related to a gravity wave. But since this pattern only shows the correlation between wind speed and precipitation I am not sure if it is straight forward to interpret the alternating pattern between positive and negative correlations as a gravity wave pattern. The existence of high mountain ranges causes up- and down-drafts and gravity waves are likely to occur when atmospheric flow passes high mountain ranges. But gravity waves require stable atmospheric conditions under which mostly no precipitation occurs. Since we focus on precipitation days these situations are not captured in the data. Since we are looking at the mean daily conditions for precipitation days for all days of a month during our study period of 13 years, we assume that a pattern caused by gravity waves in combination with precipitation would be averaged out.

R3C12: Page 12, line 1-2: This is a very general comment and does not go into the type of correlation you are dealing with in this study. I believe Spearman's R to be adequate here, but I recommend adding a word of caution, since a nonparametric measure for correlation limits the interpretation of R values. It is not a source of uncertainty as such, but should be mentioned somewhere in the manuscript (along with more details on the significance tests and the sensitivity of results to significance levels)

AR: Thank you for this remark. We are aware of the fact that ranking the data leads to a slight information loss compared to the real values. But we are sure that for our study the advantages are bigger than the disadvantages. Rank correlations are more robust against outliers and are independent from the real data. In our case it makes it easier to compare regions with very different precipitation amounts.

Technical Comments:

R3C13: There are too many grammatical errors to highlight all in this section. Furthermore, the phrasing of many sentences is confusing. I strongly suggest to let a native speaker to review the language of this manuscript.

AR: Thank you for this comment. We will carefully revise the language of the manuscript with help of a native speaker.

R3C14: Page 1, line 33: "strenghtening" instead of "strengthen"

AR: OK, done.

R3C15: Page 1, line 31-33: This sentence is confusing. Think about rephrasing it or breaking it up into two sentences.

AR: We will break up this sentence into two sentences.
Old: "This may help to estimate the impact of future climate change on precipitation development and amounts, since if a specific control in a specific region and time is identified, one would be aware that a strengthen or weakening of this precipitation control has distinct impact on precipitation development."

New: “Identifying precipitation controls may also help to estimate the impact of future climate change on precipitation variability.”

R3C16: Page 2, line 3: Do you mean “gives us the opportunity for a process based analysis of the data”?

AR: Yes, thank you.

R3C17: Page 2, line 5-7: Change to something like “Therefore, we want to examine the timing, location and strength of the influence of precipitation controls on precipitation development.”

AR: OK, done. Thank you for your suggestion.

R3C18: Page 2, line 7-8: Rephrase to something like “The aim of this study is to describe the spatial and temporal correlation of [...]”

AR: Done. New: “The aim of this study is to describe the spatial and temporal correlation of selected dynamical variables and precipitation. We want to reveal the underlying mechanisms through which the variables influence precipitation variability and therefore act as controls of precipitation variability.”

R3C19: Page 2, line 12: I suggest citations at this point when making statements about the influence of the factors being known.

AR: We will add citations in a revised version of the manuscript.

R3C20: Page 2, line 25: Abbreviations should be introduced earlier in the text when their full names are first mentioned.

AR: OK, sorry, this was a mistake maybe caused by changing the order of paragraphs.

R3C21: Page 2, line 33: Change to “correspond to”

AR: OK, done.

R3C22: Page 2, line 35: Change to “at a height”

AR: OK, done.

R3C23: Page 2, line 36: “[. . .] which strength and location [. . .]” - review the grammar here/rephrase.

AR:
Old: At the 300 hPa level we are already in a height where the westerly jet occurs, which strength and location influences the hydro-climate of the TP and central Asia (e.g. Schiemann et al., 2009).

New: The core of the westerly jet occurs at the 200 hPa level. Over the Tibetan Plateau the jet reaches down to 300 hPa and still has an effect there and also in lower levels. This was shown for the HAR by Maussion et al. (2014). The strength and location of the jet influences the hydro-climate of the Tibetan Plateau and central Asia (e.g. Schiemann et al., 2009).

R3C24: Page 3, line 7: “windward side” is more commonly used in English than “luv side” (which is still common in German literature). I recommend changing it throughout the manuscript.

AR: Thank you for this advice, we will change it.

R3C25: Page 3, line 45-47: This is not gramatically sound (see comment Page 2, line 12)

AR: We changed the sentence, see below please.
Old: i. analyse the impact of the selected dynamic controls on precipitation development spatially and temporally differentiated, where and when has which precipitation control a how strong influence,

New: i. analyse the impact of selected dynamic controls on the spatial and temporal variability of precipitation.

R3C26: Page 4, line 1-2: This is not gramatically correct.

AR: We changed the sentence, see below please.
Old: ii. examine if precipitation controls have always and everywhere in the study region the same impact or whether there are opposing effects active in different sub-regions,

New: ii. examine whether the controls act in the same way in different regions and at different times,

R3C27: Page 5, line 19: Correct to “[. . .] precipitation is falling in this region, [...]”

AR: OK, done.

R3C28: Page 5, line 25: “There” should be the start of a new sentence for this to be grammatically sound.

AR: Thank you for this comment, please see changes below.
Old: The class laying between the so called monsoonal and convective classes represents a region of mixing between monsoonal and convective classes, there we can have monsoonal precipitation and/or only solar forced convective precipitation (green). This class represents a transition zone where the monsoon can have influence but is not dominant.

New: The green class represents a transition zone between the monsoonal and convective classes where the monsoon can have an influence but is not dominant. This means that both monsoonal precipitation and/or only solar forced convective precipitation can occur.

We will also rephrase the section where the precipitation clusters are introduced to make clearer what the names of the classes mean and what makes the classes different from each other. Of course convection is dominant in the monsoonal precipitation class, but the timing of precipitation is different to that in the convective class.

R3C29: Page 5, line 30-33: This sentence is confusing and not grammatically correct. Please rephrase.

AR: Thank you for this comment, please see changes below.
Old: That there is a forcing difference between the two classes is clearly visible in the timing and strength of the precipitation maximum which is higher and later in the monsoonal class and starts during the Indian Summer Monsoon onset period and persists only for a shorter time period.

New: The timing and strength of the precipitation maximum provides an indication for different forcing. In the monsoonal class the precipitation maximum is higher, starts during the Indian Summer Monsoon onset, and persists for a shorter time period.

R3C30: Page 5, line 35: Correct to “its”

AR: OK, done.

R3C31: Page 5, line 44: Correct to “evenly” (adverb)

AR: OK, done.

R3C32: Page 7, line 30: Do you mean “This supports the interpretation [...]”?

AR: Yes. We will rephrase the sentence.

R3C33: Page 8, line 4: Correct to “Therefore”

AR: OK, done.

Anonymous Referee #4

Received and published: 23 March 2016

This paper by Julia Curio and Dieter Scherer try to demonstrate that the westerlies is an important factor influence the precipitation in the Tibetan Plateau even in the monsoon season, based on the High Asia Refined analysis. The correlation and principal components are used in this manuscript. There are five major problems in the manuscript described below. By considering these issues, I suggest major revisions.

Major issues:

R4C1: The text is not fairly organized, especially the introduction. The discussion and interpretations are superficial given the figures results. Authors need to present their work with better clarity.

AR: We will revise the entire manuscript to make it more concise, clear and easier to follow for the reader. We also will try to present our findings more clearly and to deepen the discussion.

R4C2: Authors used the HAR as the unique data for analyses, but they did not evaluate the dataset with observations on the Tibetan Plateau, and did not confirm their results with other data. The systematic analysis of stable isotopes in precipitation on the Tibetan Plateau has demonstrated the seasonal moisture origins and moisture transports. I suggest the authors to refer it.

AR: We will add a section about the uncertainties of the HAR data set and the evaluation /validation. In our last study about atmospheric moisture transport on and to the Tibetan Plateau we referred to studies analyzing the stable isotopes in precipitation to identify moisture sources and transport routes. Since this is not the topic of the current study we only referred to our former findings. In a revised version of the manuscript we will refer to these analyses to support the importance of moisture recycling on the Tibetan Plateau.

R4C3: Why these six factors are considered in this study? Winds does not mean the precipitation if there is no moisture transport with them. Authors concluded that all of these factors combined influence on precipitation. In this case, what is the main contribution of this study? Authors also said moisture recycling was important that offers more than 60% moisture for precipitation. Which one is more important, the westerlies or the recycling? It is unclear.

AR: We do not think that these two findings should be ranked. One finding is regarding the moisture sources the other regarding the dynamical processes that lead to precipitation variability.

The horizontal wind speed is not described as a factor which alone leads to precipitation. The selected controls do not cause or suppress precipitation but influence the spatial and temporal variability of precipitation. The main influence of the horizontal wind speed is cutting off deep convection, if it is not associated with enhanced moisture transport.

R4C4: Why is 300hPa for the westerlies? Authors did not clarify the precipitation heights on the Tibetan Plateau. Due to the complex topography and climate, different type of precipitation shows diversified contribution to the annual precipitation amount and it occurs at different height. It should be considered.

AR: Please see response to reviewer comment R2C5.

R4C5: This manuscript is not easy to follow because of many grammatical errors and disordered sentences.

AR: We will improve the language and sentence structure in a revised version of the manuscript.

References

Barros, A. P., Chiao, S., Lang, T. J., Burbank, D., & Putkonen, J. (2006). From weather to climate—Seasonal and interannual variability of storms and implications for erosion processes in the Himalaya. *Geological Society of America Special Papers*, *398*(02), 17 –38. doi:10.1130/2006.2398(02).

Bartholy, J., & Pongracz, R. (2010). Analysis of precipitation conditions for the Carpathian Basin based on extreme indices in the 20th century and climate simulations for 2050 and 2100. *Physics and Chemistry of the Earth*, *35*(1-2), 43–51. doi:10.1016/j.pce.2010.03.011

Bookhagen, B., & Burbank, D. W. (2010). Toward a complete Himalayan hydrological budget: Spatiotemporal distribution of snowmelt and rainfall and their impact on river discharge. *Journal of Geophysical Research*, *115*(F3), F03019. doi:10.1029/2009JF001426

Ceballos, A., Martinez-Fernandez, J., & Luengo-Ugidos, M. A. (2004). Analysis of rainfall trends and dry periods on a pluviometric gradient representative of Mediterranean climate in the Duero Basin, Spain. *Journal of Arid Environments*, *58*(2), 215–233. doi:10.1016/j.jaridenv.2003.07.002

Curio, J., Maussion, F., & Scherer, D. (2015). A 12-year high-resolution climatology of atmospheric water transport over the Tibetan Plateau. *Earth System Dynamics*, *6*(1), 109–124. doi:10.5194/esd-6-109-2015

Findell, K. L. (2003). Atmospheric controls on soil moisture-boundary layer interactions: Three-dimensional wind effects. *Journal of Geophysical Research*, *108*, 1–21. doi:10.1029/2001JD001515

Frei, C., Schär, C., Lüthi, D., & Davies, H. C. (1998). Heavy precipitation processes in a warmer climate. *Geophysical Research Letters*, *25*(9), 1431. doi:10.1029/98GL51099

Garreaud, R. D. (2007). Precipitation and circulation covariability in the extratropics. *Journal of Climate*, *20*(18), 4789–4797. doi:10.1175/JCLI4257.1

Giovannettone, J. P., & Barros, A. P. (2009). Probing Regional Orographic Controls of Precipitation and Cloudiness in the Central Andes Using Satellite Data. *Journal of Hydrometeorology*, *10*(1), 167–182. doi:10.1175/2008JHM973.1

Johansson, B., & Chen, D. (2003). The influence of wind and topography on precipitation distribution in Sweden: Statistical analysis and modelling. *International Journal of Climatology*. doi:10.1002/joc.951

Lana, X., Burgueño, A., Martínez, M. D., & Serra, C. (2006). Statistical distributions and sampling strategies for the analysis of extreme dry spells in Catalonia (NE Spain). *Journal of Hydrology*, *324*(1-4), 94–114. doi:10.1016/j.jhydrol.2005.09.013

Liu, B., Xu, M., & Henderson, M. (2011). Where have all the showers gone? Regional declines in light precipitation events in China, 1960-2000. *International Journal of Climatology*, *31*(8), 1177–1191. doi:10.1002/joc.2144

Martin-Vide, J., & Gomez, L. (1999). Regionalization of peninsular Spain based on the length of dry spells. *International Journal of Climatology*, *19*(5), 537–555. doi:10.1002/(SICI)1097-0088(199904)19:5<537::AID-JOC371>3.0.CO;2-X

Maussion, F., Scherer, D., Mölg, T., Collier, E., Curio, J., & Finkelnburg, R. (2014). Precipitation Seasonality and Variability over the Tibetan Plateau as Resolved by the High Asia Reanalysis*. *Journal of Climate*, *27*(5), 1910–1927. doi:10.1175/JCLI-D-13-00282.1

McVicar, T. R., Roderick, M. L., Donohue, R. J., Li, L. T., Van Niel, T. G., Thomas, A., … Dinpashoh, Y. (2012). Global review and synthesis of trends in observed terrestrial near-surface wind speeds: Implications for evaporation. *Journal of Hydrology*, *416-417*, 182–205. doi:10.1016/j.jhydrol.2011.10.024

Mölg, T., Maussion, F., & Scherer, D. (2014). Mid-latitude westerlies as a driver of glacier variability in monsoonal High Asia. *Nature Climate Change*, *4*(1), 68–73. doi:10.1038/nclimate2055

Numerical Recipes, The Art of Scientific Computing (Second Edition), Cambridge University Press (ISBN 0-521-43108-5).

Polade, S. D., Pierce, D. W., Cayan, D. R., Gershunov, A., & Dettinger, M. D. (2014). The key role of dry days in changing regional climate and precipitation regimes. *Scientific Reports*, *4*(4364), 8pp. doi:10.1038/srep04364

Rose, B. E. J., & Lin, C. A. (2003). Precipitation from vertical motion: A statistical diagnostic scheme. *International Journal of Climatology*, *23*(8), 903–919. doi:10.1002/joc.919

Zhang, J. W., & Atkinson, B. W. (1995). Stability and wind shear effects on meso-scale cellular convection. *Boundary-Layer Meteorology*, *75*(3), 263–285. doi:10.1007/BF00712697

List of relevant changes made in the manuscript

- We replaced the correlation plots for selected months with the plots for all months provided in the supplementary material of an earlier version of this manuscript.
- We excluded the height of the planetary boundary layer from the list of selected dynamic variables, as suggested by anonymous referee 1.
- We also removed the vertical wind speed at the model level 10 from the manuscript, because the results are very similar to the results for the 300 hPa vertical wind speed.
- We added the plots of the additional analyses conducted for the author response to the manuscript or the supplementary material.
- We added more references regarding the selection of the dynamic precipitation control.

Seasonality and spatial variability of dynamic precipitation controls on the Tibetan Plateau

Julia Curio[1,2] and Dieter Scherer[1]

[1]Chair of Climatology, Technische Universität Berlin, Berlin, Germany
[2]National Centre for Atmospheric Science, Department of Meteorology, University of Reading, Reading, UK

Correspondence to: J. Curio (j.curio@reading.ac.uk)

Abstract. The Tibetan Plateau (TP) is the origin of many large Asian rivers, which provide water resources for large regions in South and East Asia. Therefore, the water cycle on the TP and adjacent high mountain ranges, in particular the precipitation distribution and variability play an important role for the water availability for billions of people in the downstream regions of the TP.

The High Asia Refined analysis (HAR) is used to analyse the dynamical factors that influence the precipitation variability in the TP region, including the factors resulting in the enhancement and suppression of precipitation. Four dynamical fields that can influence precipitation are considered, the 300 hPa wind speed and wind speed two kilometres above ground, the 300 hPa vertical wind speed, and the atmospheric water transport. The study focusses on the seasonality and the spatial variability of the precipitation controls and their dominant patterns. Results show that different factors have different effects on precipitation in different regions and seasons. This depends mainly on the dominant type of precipitation, convective or frontal/cyclonic precipitation. Additionally, the study reveals that the mid-latitude westerlies have a high impact on the precipitation distribution on the TP and its surroundings year-round and not only in winter.

1 Introduction

The Tibetan Plateau has been called the "world water tower" (Xu et al., 2008), and is the origin of many rivers in high Asia, which provide water for billions of people downstream in South and East Asia. The TP is located in the transition zone between the mid-latitude westerlies (Schiemann et al., 2009) and the Indian and East Asian summer monsoon systems (Webster et al., 1998). The TP shapes the hydro-climate of downstream regions by its influence on the large-scale circulation (Hahn and Manabe, 1975), caused by its large extent and height.

Since precipitation is a key feature of the water cycle of High Asia, it is important to analyse the factors controlling precipitation variability. Identifying which dynamic factors influence the precipitation may also help to estimate the impact of future climate change on precipitation variability.

Previous studies have stated that precipitation over the TP is controlled by the westerlies in winter and the Indian and East Asian summer monsoon in summer (e.g. Hren et al., 2009; Tian et al., 2007; Yang et al., 2014). This assumption is derived only from the precipitation timing, but Curio et al. (2015) and Mölg et al. (2014) already shown that the mid-latitude westerlies also have an impact on the summer precipitation.

There are many studies that have explored the influence of atmospheric circulation modes, e.g. the North Atlantic Oscillation, the Arctic Oscillation, and El Nino/Southern Oscillation, on the climate and precipitation in high Asia and on the monsoon systems (e.g. Bothe et al., 2009; Liu et al., 2015; Liu and Yin, 2001; Rüthrich et al., 2015). Less attention has been paid to the underlying processes controlling the precipitation variability over the TP and the surrounding high mountain ranges.

Gelöscht: ²Department
Gelöscht: julia
Gelöscht: tu-berlin.de
Gelöscht: moisture
Gelöscht: and especially
Gelöscht: plays
Gelöscht: regions
Gelöscht: Based on the
Gelöscht: we
Gelöscht: of dynamic factors on
Gelöscht: , enhancing or suppressing
Gelöscht: development. We selected six
Gelöscht: controls, the horizontal and vertical wind speed at
Gelöscht: in about
Gelöscht: , and the planetary boundary layer height. Focus of the
Gelöscht: are
Gelöscht: se
Gelöscht: The results
Gelöscht: precipitation controls
Formatiert: Abstand Vor: 6 Pt.
Gelöscht: , often
Gelöscht: in the
Gelöscht: regions
Gelöscht: the impact of
Gelöscht: and
Gelöscht: . This may
Formatiert: Schriftfarbe: Text 1
Gelöscht: development and amounts, since if a specific control in a specific region and time is identified, one would be aware that a strengthen or weakening of this precipitation control has distinct impact on precipitation development
Formatiert: Schriftfarbe: Text 1
Gelöscht: on
Gelöscht: based
Gelöscht: on
Gelöscht: 3
Gelöscht: ed
Gelöscht: also
Gelöscht: There are many studies on the influence of atmospheric circulation modes, e.g. the North Atlantic Oscillation, the Arctic Oscillation, and El Nino/Southern Oscillation, on climate and precipitation in high Asia and on the monsoon systems (e.g. Bothe et al., 2009; Liu et al., 2015; Liu and Yin, 2001; Rüthrich et al., 2015). Less attention is drawn to the underlying processes controlling precipitation development on the TP and the surrounding high mountain ranges. ... [1]

The High Asia Refined analysis (HAR) (Maussion et al., 2014), which is the result of the dynamical downscaling of an operational analysis and which covers more than thirteen years at high spatial and temporal resolution, provides the opportunity for a process based analysis of the precipitation and its variability.

The starting point of this study is the seasonality of the precipitation over the TP and the evaluation of the factors that control the precipitation over the TP and the surrounding high mountain ranges. This focusses on the timing, location and strength of the factors that influence precipitation and its variability.

The main aim of this study is to describe the spatial and temporal correlation of selected dynamical variables and precipitation to reveal the underlying mechanisms through which the variables influence precipitation and therefore act as controls of precipitation variability.

We selected four variables as dynamic precipitation controls: horizontal wind speed at 300 hPa and in about two kilometres above ground, the vertical wind speed at 300 hPa, and the vertically integrated atmospheric water transport. It is known that these factors have an influence on precipitation variability, but on the basis of coarse resolution datasets it was not possible to analyse the relations spatially and temporally differentiated like it is now with the High Asia Refined analysis (HAR).

The different precipitation controls have effects on different spatial scales. While the horizontal and vertical wind speed at 300 hPa (WS300 and W300) are large-scale controls, the horizontal wind speed in the boundary layer (WS10) is active on the meso-scale. The atmospheric water transport (AWT) connects the large- with the meso-scale because it is effective on both scales and across large distances. We do not claim completeness for the list of precipitation controls, but assume that these four factors belong to the most important dynamic precipitation controls. It is important to keep in mind, that the precipitation controls are not independent from each other and can have combined effects on precipitation variability or neglect each other, this will not be in the focus of the current study.

In the following we will shortly introduce the selected precipitation controls and their possible impacts on precipitation variability.

The horizontal wind speed at the 300 hPa level has two main effects on precipitation variability. High WS300 can inhibit or cut off deep convection and thus supress precipitation development (e.g. Findell et al., 2003; and Zhang and Atkinson,1995). In this case only shallow convection can form which does not lead to considerable precipitation amounts. Mölg et al. (2009) showed that convective precipitation events on tropical mountain summits correspond to low horizontal wind speeds. On the other hand, higher wind speeds can have positive effects on moisture advection and orographic lifting, and can, in lower levels, enhance evaporation from the surface and therefore convection (e.g. Johansson and Chen, 2003; Roe, 2005). This process is most interesting during the warm half of the year, when surface moisture from local sources like lakes, soil moisture, the active layer of permafrost, snow and glacier melt is available. Moisture recycling plays an important role for precipitation on the TP (e.g. Araguás-Araguás et al., 1998; Trenberth, 1999), on average more than 60% of moisture needed for precipitation falling on the inner TP are provided by the TP itself (Curio et al., 2015).

The core of the Subtropical Westerly Jet (SWJ) occurs at the 200 hPa level. Over the Tibetan Plateau the jet reaches down to 300 hPa and still has an effect there and also in lower levels. This was shown for the HAR by Maussion et al. (2014). The strength and location of the jet influences the hydro-climate of the Tibetan Plateau and central Asia (e.g. Schiemann et al., 2009). Especially the precipitation seasonality in the north-western parts of the study region is related to the position of the jet (Schiemann et al., 2008). Garreaud (2007) pointed out that stronger than normal low level westerlies lead to more precipitation on the windward side of meridionally orientated mountain ranges (orographic precipitation), while high wind speeds at mountain tops leads to rather dry conditions because of intensified downdrafts. This process is called rain shadow effect. But he also shows this could lead to more precipitation on the lee

Formatiert ... [2]
Gelöscht: a gridded global data set
Gelöscht: , on a daily basis, gives us
Gelöscht: to analyse the data
Gelöscht: .
Formatiert: Schriftart:Times, Deutsch
Gelöscht: Starting
Gelöscht: precipitation
Gelöscht: on
Gelöscht: question which
Gelöscht: on
Gelöscht: Therefore, we want to examine which ... [3]
Gelöscht: on
Gelöscht: development and how strong it is. Aim
Formatiert: Schriftfarbe: Text 1
Gelöscht: between controls
Formatiert: Schriftfarbe: Text 1
Formatiert: Schriftfarbe: Text 1
Gelöscht: spatially and temporally differentiated.
Gelöscht: six
Gelöscht: ,
Gelöscht: and vertical
Gelöscht: and the height of the planetary boundary layer.
Gelöscht: development
[1] verschoben
Gelöscht: six
Gelöscht: development
[2] nach unten: The selection of precipitation control ... [4]
Gelöscht: Back and Bretherton, 2005; Garreaud, 2007 ... [5]
[1] nach oben: The different precipitation controls ha ... [6]
Gelöscht: While the horizontal and vertical wind spe ... [7]
Gelöscht: development
Kommentiert [Office1]: Since the precipitation ... [8]
Gelöscht: development
Gelöscht: .
[3] verschoben
Gelöscht: with low horizontal wind speeds. On the ot ... [9]
Formatiert ... [10]
Formatiert: Schriftfarbe: Blau
Gelöscht: ... [11]
[3] nach oben: , on average more than 60% of mois ... [12]
Gelöscht: Back and Bretherton (2005) found that th ... [13]
[4] nach unten: The negative effect of high horizon ... [14]
Gelöscht: While the positive effect occurs in region ... [15]
Gelöscht: luv

side because more cloud particles are advected and disturbances can overcome the topographic barrier with the help of higher wind speeds, which would lead to more frontal or cyclonic precipitation. This case already shows that it depends on many factors which influence each of the dynamic controls has on precipitation and that the of influence highly varies regarding time and space.

The influence of the vertical wind speed on precipitation depends on the direction of the vertical wind, whether it is an updraft or a downdraft (Rose et al., 2003). Updrafts have a positive impact on precipitation because they can boost or enhance convection and are a key element for orographic precipitation on the windward side of mountain ranges, while downdrafts (e.g. on the lee side of mountain ranges) and subsidence lead to inhibition of convection and cloud dispersal. The expectation is that we have mainly positive correlations of vertical wind with precipitation, high upward winds cause higher precipitation and higher downward winds cause less precipitation.

Atmospheric water transport (AWT) is not only a dynamic precipitation control because it is a product of atmospheric moisture content and wind speed (and direction). The positive effect of AWT on precipitation variability due to moisture supply is described in, for example, Barros et al., 2006; and Giovannetone et al., 2009. Therefore, we assume that there is always a positive correlation between AWT and precipitation. But high AWT does not automatically lead to precipitation development, what was for example shown by Curio et al. (2015) for the Qaidam Basin where the prevailing atmospheric subsidence inhibits convection.

The main objectives of the study are two-fold:

i. to analyse the impact of selected dynamic variables on the spatial and temporal variability of precipitation,

ii. to examine whether the different factors that control precipitation variability act in the same way in different regions and at different times,

iii. to gain a better understanding of the role of the mid-latitude westerlies and the summer monsoon systems on the precipitation distribution on the TP.

In the following section, we describe the data and methods used in this study. Section 3 present the precipitation seasonality on the TP and adjacent mountain ranges based on the HAR using a cluster analysis. Focus of the study is the period 2001-2013. Afterwards we analyse the correlations between the four selected dynamic variables and precipitation, regarding seasonality and spatial variability. A principal component analysis of this correlations is then used to detect the dominant patterns. The results and their uncertainties are discussed in section 4. In section 5, we draw conclusions from our study.

2 Data and methodology

2.1 The High Asia Refined analysis

This study is based on the High Asia Refined analysis (HAR). The HAR has been produced using the advanced research version of the Weather and Research Forecasting model (WRF-ARW, Skamarock and Klemp, 2008) version 3.3.1 to dynamically downscale the Operational Model Global Tropospheric Analyses (final analyses, FNL; data set ds083.2), a global gridded data set. The HAR dataset, its modelling, forcing, and re-initialization strategies are described in detail by Maussion et al., (2011, 2014). The HAR data set currently covers the period from October 2000 to September 2014 and will be updated continuously. The first domain of the HAR encompasses most parts of south-central Asia with a spatial resolution of 30 km and temporal resolution of 3 h (HAR30). High Asia and the Tibetan Plateau are the focus of a second nested domain with a spatial resolution of 10km and temporal resolution of 1 h

Gelöscht: development

Gelöscht: .

Gelöscht: luv

Gelöscht: We

Gelöscht: , because AWT delivers moisture for precipitation from remote sources to the TP (regions where precipitation occurs).

Gelöscht: The height of the planetary boundary layer (PBLH) shows the turbulent mixing of the lower atmosphere. It is influenced by solar forcing, turbulent processes, convective activity (Yang et al., 2004), moisture content and temperature of surface and air, and wind speed. Gentine et al. (2013) point out that dry soil surface accelerates the growth of the PBL. The TP has one of the highest PBLs in the world, due to its high altitude and strong solar forcing, but the TP PBL is not fully understood yet because there are only few observations. During daytime in spring and summer the PBL is higher than in the other seasons in this region (Patil et al., 2013) and can exceed heights of 3000 m or more (Ma et al., 2009; Yang et al., 2004) in some regions on the TP due to strong solar forcing and convective activity. The horizontal wind speed influences the PBLH by facilitating the m ... [16]

Formatiert: Schriftfarbe: Text 1

Gelöscht: the

Formatiert: Schriftfarbe: Text 1

Gelöscht: controls on precipitation development spa ... [18]

Formatiert ... [17]

Formatiert ... [19]

Formatiert: Schriftfarbe: Text 1

Gelöscht: if precipitation controls have always and ... [20]

Gelöscht: there are opposing effects active in

Formatiert: Schriftfarbe: Text 1

Gelöscht: sub-regions,

Formatiert: Schriftfarbe: Text 1

Formatiert: Schriftart:Times, Schriftfarbe: Text 1

Gelöscht: and

Gelöscht: for

Gelöscht: Here we first

Formatiert: Abstand Vor: 6 Pt.

Gelöscht: six

Gelöscht: precipitation controls

Gelöscht: Methods

Formatiert: Abstand Vor: 6 Pt.

Gelöscht: HAR data set

Formatiert: Abstand Vor: 6 Pt.

Gelöscht: is generated

Gelöscht: Skamarock and Klemp, 2008

Gelöscht: for

Gelöscht: downscaling of

Gelöscht: , and the validation of the results

Gelöscht:

Gelöscht: .

(HAR10). A map of the HAR10 domain and its location in the parent domain HAR30 are shown in Fig. 1. In this study we analyse the processes on the TP and the surrounding high mountain ranges and therefore use the HAR10 data only. The calculation of the vertically integrated atmospheric water transport can be found in Curio et al. (2015). For this study the HAR data are used on a daily basis.

Gelöscht:

Gelöscht: ... [21]

The HAR data set was validated by Maussion et al. (2014) by comparison with rain-gauge observations from the National Climatic Data Center (NCDC) and the satellite derived gridded precipitation data from the Tropical Rainfall Measuring Mission (TRMM). The HAR shows a slightly positive bias in comparison with station data, 0.17 mm/day for HAR10 (0.26 mm/day for TRMM 3B43 product). The comparison with TRMM shows that HAR captures the general features of precipitation seasonality, variability, and spatial distribution. Maussion et al. (2014) found that the HAR10 precipitation averaged over the domain shows 15% more precipitation than TRMM, but these differences are assumed to be related to the well- known underestimation of snowfall and light rain by TRMM. Convective precipitation is simulated in agreement with results from literature, but one has to keep in mind that the model uses a parameterization scheme for cumulus convection. A spatial resolution of 10 km is not high enough to resolve cumulus convection. The HAR is able to reproduce orographic precipitation features as documented by Bookhagen and Burbank (2010). Maussion et al. (2014) state that these qualitative considerations cannot provide a quantitative uncertainty value. Curio et al. (2015) compared the HAR30 atmospheric water transport (AWT) with ERA-Interim. They found similar patterns; the differences being related to the different spatial resolutions and thus a better representation of the underlying topography by the HAR. In the HAR data, the blocking of AWT from the Bay of Bengal by the Himalayas is more pronounced, and the results show the importance of meridionally orientated high mountain valleys for moisture supply to the Tibetan Plateau. We have compared the 300 hPa wind of the HAR10 data set with ERA-Interim. Figure R1 shows that they are in a good agreement with each other. Due to the daily reinitialization strategy used to generate the HAR data set, the wind fields in higher levels cannot evolve far away from the forcing data as this is possible for longer model runs. The question how large the uncertainties of the HAR data and especially precipitation are and how we can estimate them, is a topic which should be investigated more in detail. Since there are no other gridded data sets with a comparable high temporal and spatial resolution, the possibilities to validate the HAR are generally limited and will be subject of future research.

2.2. Methodology

The selection of precipitation controls relies on well studied relations of these factors with precipitation (e.g. Back and Bretherton, 2005; Garreaud, 2007; Shinker et al., 2006) but these controls were not investigated at high spatial and temporal resolution in high mountain Asia until now.

[2] verschoben

The current study is based on the HAR10 data set for the study period 2001-2013 (all entire years available). Starting point of this study is an analysis of the precipitation seasonality on the TP using the k-means clustering method (e.g. Wilks, 1995). The percentages of monthly contribution to annual precipitation and not the precipitation amounts were used to define seven classes with different precipitation seasonality. This has the advantage that, in an area like high Asia where the differences in precipitation amounts vary strongly between regions and seasons, the regions were made comparable by this method. We conducted the cluster analysis with other numbers of classes (5-9), but the chosen number of seven classes led to the best ratio between coherent patterns and sufficient distinction between classes. This analysis follows the approach of Maussion et al. (2014) who used the clustering to detect glacier accumulation regimes on the TP. Their input data were restricted to glaciated areas only. Our current analysis expands the data base to the entire TP and surrounding regions, using all grid points of the HAR10 domain. For all further analysis daily averaged HAR data are used. Because we are only interested in precipitation days, the data set is stratified using a daily precipitation threshold. This is done month-wise. For example, all analyses for July depend on the data basis of each July day during the period 2001-2013; these are 31*13 days, 403 days in total. Precipitation days for a grid point are defined as days with a mean daily precipitation rate of at least 0.1 mm, which is a commonly used minimum value to define precipitation days (e.g. Polade et al., 2014; Liu et al., 2011; Bartholy et al., 2010; Frei et al., 1998). The threshold was basically used to filter out numerical artefacts and not to exclude events from the data base.

The daily precipitation rate at each grid point is calculated as the mean precipitation rate for all grid points within an area of 15*15 grid points around the specific grid point, respectively. The time mask for precipitation days is then applied to the four variables used as precipitation controls. The number of precipitation days can vary distinctly between regions and seasons. Each of the dynamical variables is correlated with the precipitation using the Spearman rank correlation. This is done month-wise for all precipitation days in a specific month during the study period and for each grid point in the HAR10 data set. Using correlations avoids problems associated with the exact precipitation rates/amounts falling on the TP, which are hard to measure and to model exactly. The Spearman rank correlation uses the ranks of the values and not the values itself, which makes the correlations independent of the real data and more robust against outliers. This makes it easier to compare regions with very different precipitation amounts with each other and helps to reduce the effects of extreme events on the correlation results. We are aware of the fact that ranking the data leads to a slight information loss compared to the real values. We are sure that for our purpose the advantages are bigger than the disadvantages. Only correlations, which are significant at the 95% level, are plotted. The statistical significance of the correlations was tested using a two tailed test to determine the deviation from zero (Numerical Recipes, The Art of Scientific Computing, 1992). The calculation oft the statistical significance is described more in detail in the supplementary material. A principal component analysis (PCA) is performed for the results of the correlations with precipitation to detect the dominant relationships.

3 Results

3.1 Precipitation seasonality

Figure 2 shows the seven defined classes of precipitation regime, and the mean annual cycle of monthly precipitation percentage in each class. It is clearly visible that the TP and the surrounding high mountain ranges show a spatial variability regarding precipitation seasonality. A class with a precipitation maximum in summer and a minimum in winter is dominant on the central TP and south of the Himalayas in India, Nepal and Pakistan (blue, class 6). This class is the monsoonal precipitation class, because the precipitation percentage increases from June on, the onset period of the Indian summer monsoon. During July and August more than 50% of the annual precipitation is falling in this regions, while from October to May the monthly precipitation amount is below 5 % of the annual precipitation. The yellow class has a much broader and less pronounced summer precipitation maximum and the increasing and decreasing proceed with similar rates. The annual cycle of precipitation in this class is determined by the seasonal cycle of solar forcing and therefore convective activity. The green class represents a transition zone between the monsoonal and convective classes where the monsoon can have an influence but is not dominant. This means that both monsoonal precipitation and/or only solar forced convective precipitation can occur.

The naming convention does not mean that the monsoonal class precipitation is not of convective nature, but it should emphasize that the precipitation (development/variability) is influenced by the monsoon, which is associated with the advection of tropical air masses. The

Formatiert: Abstand Vor: 0 Pt., Nach: 12 Pt., Abstand zwischen Absätzen gleicher Formatierung einfügen, Keine Absatzkontrolle, Leerraum zwischen asiatischem und westlichem Text nicht anpassen, Leerraum zwischen asiatischem Text und Zahlen nicht anpassen

Gelöscht: .

Gelöscht: therefore

Gelöscht: on

Gelöscht: precipitation controls

Gelöscht: then

Gelöscht: ,

Gelöscht: t

Gelöscht: ,

Gelöscht: Only significant

Gelöscht: , with a level of significance of 0.05, are plotted. Following this, a principal component analysis (PCA) was performed for the correlations between controls and precipitation to detect the dominant patterns. ... [22]

Gelöscht: regarding

Gelöscht: starting point of this study is the precipitation seasonality on the TP which was analysed by Maussion et al. (2014) using the k-means clustering method (e.g. Wilks, 1995) and will be deepened in the current study. The percentages of monthly contribution to annual precipitation

Gelöscht: precipitation amounts were used to define seven classes with

Gelöscht: seasonality. This has the advantage that in an area like high Asia where the differences in precipitation amounts vary strongly between regions and seasons, the regions were made comparable by this method. We conducted the cluster analysis

Gelöscht: numbers of classes, but

Gelöscht: chosen number

Gelöscht: seven classes led to the best ratio between coherent patterns and sufficient distinction between classes

Formatiert: Schriftfarbe: Text 1

Formatiert: Keinen Abstand zwischen Absätzen gleicher Formatierung einfügen

Formatiert: Abstand Vor: 6 Pt.

Gelöscht: are

Gelöscht: intensive

Formatiert: Schriftfarbe: Text 1

Formatiert: Schriftfarbe: Text 1

Gelöscht: laying

Formatiert: Schriftfarbe: Text 1

Gelöscht: so called

Formatiert: Schriftfarbe: Text 1

Gelöscht: represents a region of mixing between monsoonal and convective classes, there we can have

Formatiert: Schriftfarbe: Text 1

Gelöscht: (green). This class represents a transition ... [23]

Formatiert ... [24]

monsoonal class is a subset of the convective class. The timing and strength of the precipitation maximum provides an indication for different forcing. In the monsoonal class the precipitation maximum is higher, starts during the Indian Summer Monsoon onset and persists for a shorter time period.

The monsoonal class is divided into a northern and southern part by the Himalayas. The grey-blue class experiences its precipitation maximum in winter and is dominated by the influence of the mid-latitude westerlies. This class occurs mainly in the Pamir/Karakoram/western Himalayas (PKwH) region, as one coherent pattern, and additionally in the eastern part of the Tarim Basin. The precipitation maximum is much lower, but the minimum values are higher than in the classes dominated by summer precipitation, which shows that the intra-annual variability is lower, the values vary between 15% and 5%, but are never below 5% in the mean. This could lead to the assumption that the influence of the mid-latitude westerlies is more constant year-round, while the monsoon has a stronger but temporally more limited influence on precipitation on the TP.

The light blue class exhibits a more evenly distributed seasonality of precipitation, during spring and summer with a minimum in November. This class surrounds the grey-blue cluster, at the southern flank of the western Himalayas (western notch), in the south-eastern TP, and in the eastern Tarim Basin. It is interesting that the region in the south east of the TP, where the Brahmaputra Channel enters the TP, belongs to a different class than the surroundings, which are divided between the three convectively dominated classes, blue, yellow and green. Maybe there is stronger influence by AWT, which would make this region more similar to the surrounding of PKwH region regarding the factors controlling precipitation variability. Another possible reason could be the occurrence of extra-tropical cyclones which propagate eastward along the Himalayas and are then terrain-locked by the eastern notch of the Himalayas (Norris et al., 2015). This would lead to higher moisture supply to the region and therefore higher amounts of orographic precipitation. This kind of terrain locking of the westerly flow in winter is described in detail for the western notch of the Himalayas by Norris et al. (2015). This mechanism would explain the higher shares of winter precipitation in the region around the Brahmaputra channel and the affiliation to the same class occurring at the southern flank of western Himalayas in the western notch.

The remaining two classes, red and purple, almost only appear in the Tarim Basin. They are both characterized by a spring and early summer precipitation regime, but also show some differences. The amount of precipitation in the purple class increases sharply from March to May/June were the maximum with a value of slightly above 20% occurs. The decrease is even sharper so that in July already only 6 % of the annual precipitation occur. The annual cycle of the red class seems to be delayed relative to the purple one and the period of maximum precipitation is only one-month long. In spring the values are lower but higher in late summer and autumn, while they are almost the same during winter.

The high mountain ranges of the Himalayas and Kunlun and Qilian Shan exhibit a complex structure of different classes over relatively short distances and therefore exhibit no coherent patterns. This holds true also for the border area between the Karakoram and the Tarim Basin. The mountainous region of the Pamir and Karakoram are represented by only one class, which implies that this region is mainly influenced by one atmospheric forcing (mid-latitude westerlies) or that different controls have the same impact in this region. The other mountain ranges lie in regions where an interplay of different controls occur, and the temporal and spatial variability is larger on smaller scales.

3.2 Correlation of dynamic variables and precipitation

3.2.1 Horizontal wind speed

a) Horizontal wind speed at 300 hPa (WS300)

Gelöscht: That there is a forcing difference between the two classes is clearly visible in the
Formatiert: Schriftfarbe: Text 1
Gelöscht: which is higher and later in
Formatiert: Schriftfarbe: Text 1
Gelöscht: and
Formatiert: Schriftfarbe: Text 1
Gelöscht: period
Formatiert: Schriftfarbe: Text 1
Gelöscht: only
Formatiert: Schriftfarbe: Text 1
Formatiert: Schriftart:Arial, 16 pt, Schriftfarbe: Text 1, Deutsch
Gelöscht: The monsoonal class is divided in a northern and southern part by the Himalayas.
Formatiert: Schriftart:Times, Schriftfarbe: Text 1, Deutsch
Formatiert: Abstand Vor: 0 Pt., Abstand zwischen Absätzen gleicher Formatierung einfügen
Gelöscht: seasonality, with
Gelöscht: precipitation and
Gelöscht: occurs as a frame for
Gelöscht: development.
Gelöscht: ,
Gelöscht: a bit
Gelöscht: against
Formatiert: Abstand Vor: 0 Pt., Abstand zwischen Absätzen gleicher Formatierung einfügen
Gelöscht: on
Gelöscht: may
Gelöscht: s
Gelöscht: .
Formatiert: Zeilenabstand: 1.5 Zeilen
Gelöscht: controls
Formatiert: Schriftart:Arial
Gelöscht: We only show the months with the most prominent features. Figures with the correlation of each dynamic control with precipitation for all months are provided in the supplemental material for completenes ... [25]

The correlations between WS300 and precipitation are shown in Figure 3. There are high positive correlations in winter in the PMwH region, this is the time of the year when the majority of precipitation falls in this region (e.g. Curio et al., 2015; Maussion et al., 2014). The precipitation in the PMwH region is mainly cyclonic/frontal precipitation and is associated with western disturbances (Dimri et al., 2015). There are only negative correlations in the southern and eastern parts of the TP in winter, which enlarges over spring and covers mainly the whole central and north-eastern TP and large parts of the central Himalayas with the highest negative correlations in the central TP. The reason for the negative correlations in these regions is that they are dominated by convective precipitation (e.g. Maussion et al., 2014) and higher wind speeds in winter inhibit the deep convection. This also explains why there are almost everywhere negative correlations in summer. The region of negative summer correlations covers almost the same area as the convective and monsoonal precipitation classes (Fig. 2) combined, so the impact of WS300 explains some of the precipitation classes. In spring there is a second region with positive correlations north of the TP in the Tarim Basin and the bordering Kunlun and Qilian Shan. This area is reached by the northern branch of the mid-latitude westerlies which delivers moisture for precipitation. The area around the Brahmaputra Channel exhibits slightly positive correlations, due to enhanced moisture transport by higher wind speeds. The region of high positive winter correlations exhibits no or slightly positive correlations in only a small area in summer and in some parts of the region the positive correlations are replaced by negative ones. Since there is a non negligible amount of precipitation falling in this region in summer (~ 20-40%, see cluster 0 and 5 in Fig. 2), the lag/absence of positive correlations and the occurrence of negative correlations means that a different factor controls precipitation variability and/or the same control works in a different way due to higher shares of convective precipitation, especially in the eastern parts of the Pamir Karakoram region.

b) Horizontal wind speed at model level 10 (WS10)

Figure 4 shows, that the correlations between WS10 and precipitation are positive in the PMwH region in winter as they are for WS300, but the region is larger, especially the region with correlations > 0.6. The reason for the positive correlations is again the enhanced moisture supply due to higher wind speeds and therefore also more orographic precipitation. The positive correlations in the Brahmaputra Channel region (and south of it) are more pronounced and the structure of the Brahmaputra Channel itself is clearly visible. The moisture supply is enhanced due to strengthened winds from the south, bringing moisture from the Indian Ocean to the Himalayas. There are high positive correlations between the WS10 and precipitation over the Tibetan Plateau in summer, while the correlations with WS300 are negative in summer. This is because of the fact that the wind speed in the boundary layer can enhance evapotranspiration from the surface (e.g. lakes; snow, glacier and permafrost melt), which leads to more moisture in the lower atmosphere available for precipitation. This correlation again emphasizes the importance of moisture recycling on the TP. In winter the correlations on the TP are mainly negative because the effect of enhanced evapotranspiration is not active due to the fact that all potential moisture sources are frozen during this time of the year. Strong negative correlations occur south of the Himalayas and in northern parts of India in summer. When the air flow from the south hits the mountain barrier parts of the flow are redirected southeast and northwest. The flow becomes divergent which forces the air above to decent, which in turn leads to unfavourable conditions for growing convection and therefore precipitation.

3.2.2 Vertical wind speed

The correlations between vertical wind speed at 300 hPa (Fig. 5) and precipitation are mainly positive due to the positive effect of ascending air motion on precipitation development, as

Gelöscht: provided

Gelöscht: for selected months.

Formatiert: Abstand Vor: 6 Pt.

Gelöscht: .

Gelöscht: T

Gelöscht: Curio et al., 2015; Maussion et al., 2014). The precipitation in this region is mainly cyclonic/frontal precipitation, which benefits from enhanced moisture supply due to higher wind speeds. On the TP we have only negative correlations in the southern and eastern parts in winter, while this area

Gelöscht: Reason

Gelöscht: this is

Gelöscht: dominance of

Gelöscht: in this region

Gelöscht:). Higher

Gelöscht: and therefore have a negative effect on precipitation development

Gelöscht: has

Gelöscht: shape like

Gelöscht: put together

Gelöscht: u

Gelöscht: t

Gelöscht: r

Gelöscht: which lays

Gelöscht: to

Gelöscht: in

Gelöscht: , because

Gelöscht: almost no

Gelöscht: (

Gelöscht: -

Gelöscht: % of annual

Gelöscht:) during summer months in

Gelöscht: /

Gelöscht: (Maussion et al., 2014).

Gelöscht: (February) like

Gelöscht: Reason

Gelöscht: here

Formatiert: Abstand Vor: 6 Pt., Keine Absatzkontrolle, Leerraum zwischen asiatischem und westlichem Text nicht anpassen, Leerraum zwischen asiatischem Text und Zahlen nicht anpassen

Gelöscht: in

Gelöscht:) and model level 10 (not shown because of high similarity; see supplemental material

Gelöscht: like assumed

expected, especially in summer when most of the precipitation is convective. Therefore, the positive correlations are higher in summer than in winter when almost no precipitation falls on the TP, although the mean vertical wind speeds (up- and downdrafts) are higher in winter than in summer (Fig. 6). This shows that higher values of one precipitation control alone do not necessarily lead to higher correlations and therefore more precipitation, but that usually other conditions favourable for precipitation development have to occur. This supports the interpretation that precipitation variability is mostly caused by combined effects of different precipitation controls.

The high mountain ranges of the Pamir and Karakoram show a pattern of alternating positive and negative correlations between vertical wind speed and precipitation. It was expected that the correlations between the vertical wind speed would be positive at both sides of the mountain ranges. But the negative correlations can be explained physically. If an air flow hits a mountain range, the barrier causes orographic induced flow patterns, with updrafts on the windward side and downdraft on the lee side of the mountain range. This causes the precipitation to be smaller on average on the lee side because the downdrafts supress precipitation development. In the case of a stronger horizontal flow to the mountains there is stronger moisture advection and orographic precipitation and therefore the downdrafts on the lee side are no longer able to supress precipitation. This leads to the simultaneous occurrence of precipitation and downdrafts which is the reason for the negative correlation patterns on the lee side of mountain ranges found in the western parts of the study region.

3.2.3 Atmospheric water transport (AWT)

Figure 7 shows the correlations between AWT and precipitation. The entire study region is dominated by positive correlations during the year (Fig. 7). The highest positive correlations occur in winter and early spring in the PKwH region, where the correlation coefficient exceeds 0.8 in most regions. This is the time of the year when the maximum precipitation occurs in this region (Fig. 2). The annual contribution of convective precipitation in this region is below 10% (Maussion et al., 2014), but the region exhibits orographic precipitation triggered by the advection of moist air masses with the westerly flow and westerly disturbances (Cannon et al., 2014). Therefore, higher moisture supply leads naturally to more precipitation. The positive correlations in the western parts of the study region persist during the course of the year, even if their extent and strength varies. The positive correlations extend to the TP, the whole Himalayan arc, and along the northern border of the TP (Kunlun and Qilian Shan). These seem to be the moisture supply routes along the branches of the mid-latitude westerlies.

A second centre of positive correlation which is persistent is found in the extreme southeast of TP, the region where the Brahmaputra Channel enters the TP. This region exhibits less convective precipitation on annual time scales (Maussion et al., 2014), but it is surrounded by regions with high convective precipitation rates. This explains the fact that this region belongs to a different precipitation seasonality class than its surroundings (Fig. 2). In January and February, the Himalayan arc exhibits mostly positive correlations and connects the area in the western parts of the domain with the other positive centre in the south-eastern TP around the Brahmaputra channel.

The spatial minimum of the positive correlations occurs in May, whereas the correlations are very high (r > 0.6) in the western and south-eastern centres. In May the central TP exhibits no significant correlations which may be caused by the fact that the AWT is very low on the TP in May (Curio et al., 2015). From then on the area with positive correlations enlarges but the strength of correlation decreases.

The minimum values of the positive correlations occur in July and August. But then there are positive correlations in the central TP, but they are not as high as in the western and south-eastern parts of the domain during winter and spring. This shows that the precipitation during

Gelöscht: points out/emphasizes

Formatiert: Schriftfarbe: Automatisch

Formatiert: Schriftfarbe: Automatisch

Gelöscht: assumption

Formatiert: Schriftfarbe: Automatisch

Gelöscht: development

Formatiert: Schriftfarbe: Blau

Formatiert: Schriftfarbe: Text 1

Formatiert: Abstand Vor: 0 Pt.

Gelöscht: negative correlations in the high

Formatiert: Schriftfarbe: Text 1

Gelöscht: Karakorum in winter could be an aggregation problem, due to

Formatiert: Schriftfarbe: Text 1

Gelöscht: use of daily means. This

Gelöscht: the case if we, for example, have a day with strong downdrafts in the mean, but during a shorter time

Formatiert: Schriftfarbe: Text 1

Gelöscht: day we have updrafts leading to precipitation, which are not seen in the mean for the day. Other possible reasons for

Formatiert: Schriftfarbe: Text 1

Formatiert: Schriftfarbe: Text 1

Gelöscht: could be large systems of frontal/cyclonic precipitation, which can still rain

Formatiert ... [26]

Gelöscht: , where as a consequence of the flow over the mountain ranges already

Formatiert: Schriftfarbe: Text 1

Gelöscht: occur.

Formatiert: Schriftfarbe: Text 1

Gelöscht: would lead

Formatiert ... [27]

Gelöscht: and precipitation, and therefore

Formatiert: Schriftfarbe: Text 1

Gelöscht: correlations

Formatiert: Schriftfarbe: Text 1

Gelöscht: provides…hows the correlations between AWT and precipitation. The entire study region is dominated by positive correlations during the year (Fig. 7), like we assumed before. There are only few regions and months where negative correlations occur, in the Tarim Basin during winter, at the central Himalayas (and the southern slopes) during summer.…. The highest positive correlations occur in winter and early spring in the PKwH region, where the correlation coefficient r …xceeds 0.8 in large areas…ost regions. This is the time of the year where… the maximum precipitation maximum …ccurs in this region (Fig. 2). The annual p…ontribution of convective precipitation in this regi ... [28]

Gelöscht: ,… t…his region exhibits also …ess conv ... [29]

Gelöscht: now

Gelöscht: now we have …hen there are positive ... [30]

this time of the year is mostly convective and that the moisture is coming from local sources, so that the advection of moist air masses is less important. In large areas of the domain the precipitation maximum occurs in July and August, ~30% of the annual precipitation fall on the central and southern TP during this time (Maussion et al., 2014).

The regions where the highest positive correlations occur are the regions where the precipitation maximum occurs during winter, matching the grey-blue precipitation seasonality class (Fig. 2). There are only a few regions and months where negative correlations occur, in the Tarim Basin during winter, and in the central Himalayas and northern India during summer.

3.3. Principal components

So far the spatio-temporal variability of correlation between dynamical variables and precipitation for the TP and surrounding high mountain ranges have been discussed. To detect the dominant patterns in the relationship between the different variables and precipitation and to find the time of the year a control is most efficient, we conducted a principal component analysis (PCA) for each of the correlation sets. Because the dominant modes are the main interest only the first two principal components (PCs) are analysed, which typically explain most of the variance of the data and also can explain important processes. For completeness, plots for all PCs can be found in the supplemental material of this study. The explained variance of PC1 lies between 40% and 50% and at around 20% for PC2 for all sets of correlations. The higher PCs explain lower shares of variance, less than 10% already for PC3 and only 1% for PC12.

Figure 8 shows the scores of the first two principal components for the correlation between WS300 and precipitation and their monthly loadings. PC1 shows a pattern which looks like the winter pattern of the correlations in the western parts of the study region, the spring pattern of the northern region, and the summer pattern of the TP were combined. This is confirmed by the annual cycle of loadings for PC1. The highest positive loadings occur in winter and spring, which means that these months have the largest share of the dominant pattern. The loadings are high all year-round but highest in spring and lowest in July. This implies that this pattern is not particularly influenced by the monsoon system or if so just in the onset period. We assume that the still relatively high loading is a result of the fact that there are high solar forcing and therefore convective activity on the TP which is negatively influences by higher wind speeds at 300 hPa. The loadings of the second PC (PC2) show a completely different annual cycle. They are strongly negative in winter and strongly positive in summer, it is just in the transition seasons that the loadings are around zero. For this pattern winter and summer play a similar role, even with opposing arithmetic signs. This is an annual cycle pattern. The first two PCs together account for ~ 60% of the total variance of the data.

The first PC (PC1) for the correlation between WS10 and precipitation (Fig. 9a) shows a pattern dominated by the winter and early spring situation, high positive scores in the PKwH region and the region around the Brahmaputra Channel and negative scores on the central and eastern TP. The loadings (Fig. 9b) are very high (~ 0.8) from November to April. Only in July and August the loadings are slightly negative. The positive correlations during summer on the TP are not visible in PC1, they occur in PC2 which has loadings that have a direct opposing annual cycle, meaning high positive values in Summer and slightly negative in winter. The first two PCs together explain ~ 65% of the variance in the data.

All months exhibit high loadings for PC1 of the correlation between the vertical wind speed and precipitation. Fig. 10 shows the scores and the loadings of the first two PCs for the correlation of W300 with precipitation. Summer and early autumn conditions have the largest impact, while loadings are lowest in winter, but still positive. Therefore, the high positive correlations in summer on the TP and in the lowlands south of the Himalayas are the dominant pattern, meaning that the vertical wind speed as a precipitation control is most effective during

Gelöscht: whereby

Gelöscht: are falling

Gelöscht: . ... [31]

Gelöscht: We described

Formatiert: Abstand Vor: 6 Pt.

Gelöscht: controls

Gelöscht: .

Gelöscht: leading or

Gelöscht: this relations

Gelöscht: out in which

Gelöscht: we are interested in

Gelöscht: we

Gelöscht: analyse

Gelöscht:),

Gelöscht: set. The patterns in the higher PCs, which

Gelöscht: , will be subject of a further study.

Gelöscht: Explained

Gelöscht: 10 provides the maps of

Gelöscht: we have layered

Gelöscht: .

Gelöscht: corroborated

Gelöscht: on

Gelöscht: very much

Gelöscht: rather

Gelöscht: we have

Gelöscht: has a negative correlation to high

Gelöscht: highly

Gelöscht: highly

Gelöscht: of

Gelöscht: 11a

Gelöscht: which is

Gelöscht: 11b

Gelöscht: (both levels)

Gelöscht: 12

Gelöscht: , the PCs for the correlation between W10 and precipitation are not shown because of high similarity to W300.

Gelöscht: strongest

that time of the year, but has a mostly positive impact on precipitation year-round. PC2 exhibits much lower values. The annual cycle of the loadings shows, that winter and summer both have high loadings (~ 0.5), but with different signs, positive in summer and negative in winter. Spring and autumn exhibit very low factor loadings and are more or less only transition periods between winter and summer. The first two PCs together explain ~ 70% of the variance in the data.

The loadings of the first two PCs of the correlation between AWT and precipitation (Fig. 11b) exhibit a similar annual cycle as the loadings of the correlation between WS300 and precipitation. For PC1 the loadings are high (between 0.6 and 0.9) in winter, spring and autumn and low in summer (~ 0.2). This again emphasizes the finding that AWT is a precipitation control mainly in regions and seasons where moisture advection and frontal/cyclonic precipitation is dominant. The pattern of PC2 (Fig. 13a) is important mainly by summer months (loadings > 0.8 in July and August), while the winter months exhibit negative loadings.

In summary, the annual cycle of the loadings for each of the first two PCs, show a similar annual cycle. PC1 is mostly dominated by all seasons except summer, and mainly by the winter and spring situations. Whereas PC2 is determined by summer conditions. Winter conditions also have high loadings but with negative sign, while spring and autumn only represent transition periods between these situations.

4 Discussion

4.1. General discussion of results

A main result of the current study is the high negative correlations between the 300 hPa horizontal wind speed and precipitation on the TP. This confirms the findings of Mölg et al. (2014), who showed that the flow strength at the 300 hPa level above the TP, during the onset period of the Indian Summer Monsoon, exhibits strong negative correlations with precipitation, and explains 73% of the inter-annual mass balance variability of the Zhadang glacier, located at the Nyainqenthangla range in the central TP. They argue that weak flow conditions favour convective cell growth. This together with the high positive correlations, in regions and seasons where frontal/cyclonic precipitation is dominant, shows the strong influence of the Subtropical Westerly Jet (mid-latitude westerlies) not only on the western parts of the study region but also on the TP itself, which previously has mostly been described as mainly influenced by the monsoon system (Hren et al., 2009; Tian et al., 2007; Yang et al., 2014).

Previous studies have stated that the precipitation on the TP is controlled by the mid-latitude westerlies in winter and the Indian and East Asian summer monsoon in summer (e.g. Hren et al., 2009; Tian et al., 2007; Yang et al., 2014). This assumption is based only on precipitation timing, but Curio et al. (2015) and Mölg et al. (2014) have already shown that the mid-latitude westerlies also have an impact on summer precipitation. The current study highlights their findings by the detection of the negative influence of the high horizontal wind speeds on precipitation (development, variability, amount) on the TP in summer.

Spiess et al. (2015) showed that in summer, increased horizontal wind speeds at 400 hPa have a positive effect on the height of the equilibrium line altitude at glaciers in different regions on the TP, they assumed that this could be caused by a reduction of convective precipitation due to high wind speeds. Exactly this process is shown by the strong negative correlations between horizontal wind speed at 300 hPa and precipitation in summer on the TP (Fig. 3).

The identified positive correlations of the wind speed in the boundary layer with precipitation in summer on the TP agree with the findings of Back & Bretherton (2005) who detected positive correlations between near surface wind speed and precipitation only when convection can be triggered easily. Their study region was the Pacific ITCZ, but we assume that their findings are

Gelöscht: both

Gelöscht: algebraic

Gelöscht:

Gelöscht: 3

Gelöscht: like

Gelöscht: composed

Gelöscht: Regarding the correlation between PBLH and precipitation the dominant pattern PC1 (Fig. 14), which explains ~47% of the variance in the data, is dominated by the spring, which is clearly visible by comparing the pattern of PC 1 with the correlations in May (Fig. 8). All other months exhibit high positive loadings (>0.5), too, but August has the lowest share. The dominant pattern represents the spring pattern, which shows the transition between the winter (positive correlations) and the summer conditions (negative correlations). PC2 is mainly influenced by the high negative correlations dominant summer. The winter months exhibit high negative loadings. The different behaviour above the large lakes on the central TP is visible in both PCs.

Formatiert: Abstand Vor: 0 Pt.

Gelöscht: also

Gelöscht: arithmetic

Gelöscht:

Formatiert: Abstand Vor: 18 Pt.

Formatiert: Schriftart:Arial, Deutsch

Gelöscht:

Formatiert: Abstand Vor: 12 Pt.

Gelöscht: One

Formatiert: Abstand Vor: 6 Pt.

Gelöscht: are

Gelöscht: in 300hPa

Gelöscht: Mölg et al. (2013)

Gelöscht: during this period in the regions influenced by monsoon

Gelöscht: They only explain the correlations the other way round and

Gelöscht: favours

Gelöscht: detected in the current study

Gelöscht: was so far

Gelöscht: s

Gelöscht: 2013)

Gelöscht: d

Gelöscht: have

[5] verschoben

Formatiert: Schriftfarbe: Automatisch

Gelöscht: shown

also valid for the TP in summer, where the convective activity is high and enough moisture is available at the surface.

The fact that the positive correlation of AWT with precipitation in summer on the central TP are not as high as in the western parts of the study region in winter, means that here the convection is able to produce precipitation using the moisture from local sources, which emphasizes the importance of moisture recycling, as shown by Curio et al. (2015) using HAR data and by Chen et al. (2012), Joswiak et al. (2013) and Kurita and Yamada (2008), among others. Nevertheless, AWT still has a positive effect on precipitation, but it is not an essential control during this time of the year on the central TP.

Additionally, we calculated the vertically integrated atmospheric moisture content for the HAR and repeated the calculation of correlation for this variable. The results (Fig. S5; see supplementary material) show high positive correlations between the atmospheric moisture content and precipitation throughout the year, as expected. The correlation patterns can only explain parts of the precipitation variability on the TP. This highlights how highly effective the dynamic controls are on precipitation variability, differentiated in space and time.

4.2 Sources of uncertainties

As always the uncertainty of the results mainly depends on the accuracy of the data itself, the aggregation of hourly data to daily means, and the statistical methods used to analyse the data. The HAR precipitation and other variables, e.g. wind speed and direction, and temperature, have been validated against other gridded data sets, global reanalyses and remote sensing data, and observations from weather stations by Maussion et al. (2011, 2014), as described in section 2.1.

NCDC station data were used to compare the results of the precipitation clustering approach with observations. Figure 12 shows the precipitation classes for the station data, and for the associated HAR grid points, and whether the obtained cluster regarding the mean annual cycle of monthly precipitation contribution to annual precipitation match (green dots) or not (red dots). 27 of the 65 stations (41.5%) fall in the same cluster as the nearest HAR grid point. For 38 stations (58.5%) this is not true, but most of them fall in cluster with very similar annual cycle or in cluster which are spatially very close to the cluster to which the HAR grid point belongs. This is especially the case in the mountain regions in the western, the south-eastern, and north-eastern parts of the domain where at least four different cluster occur on very small spatial scales. Table 1 shows which percentage of the stations, which all should be in one specific class regarding their associated HAR grid points, falls in which of the seven possible classes. One has to take into account that there is always a distance up to a few kilometres between the NCDC stations and the respectively associated HAR grid point. This also can cause huge differences between the elevation/altitude of stations and grid points due to the complex topography of the study region, which in turn has an effect on the precipitation distribution. Additionally, the quality of the station data is not always satisfying and the time series often show gaps, leading to a smaller data base.

The HAR10 and ERA-Interim wind speed at 300 hPa of has been compared. They are in a good agreement with each other (Fig. S6; see supplementary material). Due to the daily reinitialization strategy used to generate the HAR data set, the wind fields in higher levels cannot evolve far away from the forcing data as this is possible for longer model runs.

We decided to use the wind speed at the 300 hPa level because the wind shear in this height more strongly suppresses deep convection than at the 200 hPa level where the core of the jet lays. Also we assumed that the results would not change overall using the wind speed in 200 hPa. To proof that, we repeated the correlation analysis between wind speed and precipitation for the wind speed at 200 hPa (Fig. S7; see supplementary material). The results are very similar. The correlations at the 300 hPa level (Fig. 3) are slightly higher because the negative effect of higher wind speeds on precipitation by cutting off deep convection is higher at this

Gelöscht: t

Gelöscht: already with

Gelöscht: great

Gelöscht: like

Gelöscht: has

Gelöscht: Spiess et al. (2015) showed that in summer

Formatiert: Abstand Vor: 18 Pt.

[5] nach oben: increased horizontal wind speeds at 400 hPa have a positive effect on the height of the equilibrium line altitude at glaciers in different regions on the TP, they assumed that this could be caused by a reduction of convective precipitation due to high wind speeds. Exactly this process is shown by the strong negative correlations between horizontal wind speed at 300 hPa and precipitation in summer on the TP (Fig. 3).

Formatiert: Schriftfarbe: Text 1

Gelöscht: ... [32]

Formatiert: Abstand Vor: 6 Pt., Keinen Abstand zwischen Absätzen gleicher Formatierung einfügen

Gelöscht: the

Gelöscht: were

Gelöscht:).

Gelöscht: Due to the use of

level than in 200 hPa.

We varied the k for clustering from 5 to 9 (Fig. S8; see supplementary material). We found 7 to be the optimal k for the recent study since it gave us good coherence within the classes and sufficient distinctions between them, like you say and we state in the manuscript. We determined this qualitatively by looking at the plots for the different numbers of clusters. We first conducted the cluster analysis with 5 (Fig. S8 (a)) clusters like Maussion et al. (2014). But since we included a much higher number of grid points (we analysed the entire Tibetan Plateau), the results for the areas included in both analyses look slightly different especially in the Karakoram and Tien Shan. By increasing the number of cluster to 6 (Fig. S8 (b)), one cluster that covers most parts of the northern part of the study region, northern Tibetan Plateau and Tarim Basin, breaks up in two cluster. Setting the number to 7 (Fig. S8 (c)), we get more variation in the Karakoram and Tien Shan which looks more similar to the cluster distribution achieved by Maussion et al. (2014). Using a higher number of clusters (Fig. S8 (d) and (e)) led to the occurrence of more clusters of smaller size which are not as distinct from each other as the larger ones. In general, it would be interesting to have more cluster to get a higher spatial differentiation. But by increasing the cluster number the spatial coherence decreases and therefore the interpretability also decreases. We decided to use seven clusters as a compromise between higher spatial differentiation and less spatial coherence. Since the core areas of the clusters stay stable while changing the number of clusters we assume that the clustering approach is suitable to analyse the seasonality of precipitation on the TP.

Of course using different parameterizations and higher spatial resolutions would change the precipitation values and the spatial and temporal distribution of the precipitation. But we assume that this would not change the the main results of this study since we use rank correlations which are independent of the mean values and scaling of the input variables.

Using correlations we avoid problems regarding the exact precipitation rates falling on the TP. Additionally the use of the monthly percentage of annual precipitation as input for the cluster analyses, to detect the precipitation seasonality in different regions of the TP, makes it possible to compare regions, which exhibit distinct different precipitation amounts. This is a general aspect to keep in mind, the decision to use mean daily data therefore has advantages and disadvantages. A major advantage is the possibility to analyse the processes from a climatological perspective, which can not be done on the basis of monthly data. But, it is clear that some information is lost by aggregation from hourly to daily data. To test, how sensitive the results are regarding the use of a different significance levels, we repeated the analysis with the significance level 0.01 for the correlation between wind speed in 300 hPa and precipitation (Fig. S8) and compared the results with the results gained using 0.05 as significance level (Fig. 3). The resulting patterns do not change very much. The areas with negative and positive correlations are a little bit smaller, but the changes occur where the values are already lower (at the borders of the correlation patterns). The regions with the highest correlations stay stable and even small areas of positive or negative correlations do not disappear.

The number of precipitation days on which all analysis depends is variable regarding the analysed months and regions, but we assume that the condition of at least 13 precipitation days per grid point, applied for of all days of a specific month during the study period 2001-2013, respectively, ensures a reasonable data basis. Grid points which do not match this criterion are excluded from further analysis.

Since we only look at the first two PCs, it is possible that mechanisms controlling precipitation, which appear in higher PCs, are not considered in this study. The current study is limited to dominant patterns and thereby to the first two PCs, because they together explain more than 60% of the variance of the data. Patterns with lower explained variance and transient patterns will be subject of a subsequent study.

Formatiert: Abstand Vor: 0 Pt., Abstand zwischen Absätzen gleicher Formatierung einfügen, Keine Absatzkontrolle, Leerraum zwischen asiatischem und westlichem Text nicht anpassen, Leerraum zwischen asiatischem Text und Zahlen nicht anpassen

Gelöscht: on

Gelöscht: data process based

Gelöscht: view

Gelöscht: could

Gelöscht: . For example, it is not clear whether

Formatiert: Schriftfarbe: Text 1

Formatiert: Schriftfarbe: Text 1

Formatiert: Schriftfarbe: Text 1

Gelöscht: between the vertical wind speed and precipitation in the PKwH region are caused by a plausible physical process as described in section 3.2.2

Formatiert: Schriftfarbe: Text 1

Gelöscht: by the aggregation from hourly to daily resolution, which could mask out vertical wind speed conditions favourable for precipitation due to information loss

Formatiert: Schriftfarbe: Text 1

Formatiert: Schriftfarbe: Text 1, Deutsch

Gelöscht: In general, when interpreting correlations, one has to keep in mind that correlation not automatically can be interpreted as causality.

Gelöscht: only

Gelöscht: only

Gelöscht: on

5 Conclusion

Gaining a better understanding of the relationship between dynamical variables and precipitation and the underlying processes is important since precipitation is the key element of the hydrological cycle of the TP and surrounding high mountain ranges. Precipitation variability has a large impact on the water availability in the densely populated downstream regions of India, Pakistan and south-east Asia, by directly governing river runoff by precipitation or with a time lag by snow melt.

This study shows that different factors influence precipitation in different regions of the TP and adjacent high mountain ranges during different times of the year and in different ways. For example, the 300 hPa wind speed has a positive effect in the western parts of the study region in winter and spring, while it has a negative effect on precipitation on the TP during summer. This clearly shows that the impact of the mid-latitude westerlies is strong, not only in winter by enhancing moisture advection for orographic and frontal precipitation in the western parts of the study region, but also by cutting of deep convection during summer on the TP and in other regions and seasons where and when precipitation is mainly convective.

The negative effect of high horizontal wind speeds on precipitation plays an important role in regions and seasons which are dominated by convective precipitation e.g. the Tibetan Plateau in summer (Maussion et al. 2014). The positive effect occurs in regions with mainly frontal/cyclonic or orographic precipitation. Precipitation benefits from enhanced moisture transport by strengthened atmospheric flow, especially when the moisture flow is lifted up by orographic forcing. This plays an important role in our study region because of the high mountain ranges surrounding the Tibetan Plateau.

Therefore, the TP and the entire study region can be partitioned by considering the dominant form of precipitation that occurs, cyclonic/frontal or convective precipitation. This enables us to more clearly determine the relevancy/importance of the monsoon system and the mid-latitude westerlies for the precipitation distribution. The classification of precipitation has been determined by cluster analysis and shows a mostly monsoonal influenced class, a convective class, and a hybrid class in between. This highlights that it is not possible to draw an exact distinction for the monsoon extent and that there will always be a relatively broad area between monsoonal influenced precipitation and solely convective dominated precipitation caused by the inter-annual variability of monsoon strength and other factors.

Perhaps it is possible to say that the precipitation on the central TP in summer is influenced by the monsoon system regarding moisture supply, however moisture recycling is also important, and the mid-latitude westerlies act as a control regarding suppression or enhancement of precipitation due to the strong negative effect of high horizontal wind speeds on the development of deep convection.

A next step will analyse the combined effects of precipitation controls, since the current study has shown that the controls are not independent of each other. We intend to use a combination of PCA of the detected dominant patterns and cluster analysis to detect control regimes, as in Forsythe et al. (2015), to obtain a climate classification for the Himalayan arc and its surroundings. These regimes can perhaps help to explain regional features of glacier mass balance, like the so-called Karakoram anomaly (e.g. Hewitt, 2005), or observed lake level changes (e.g. Liu et al., 2010; Zhang et al., 2011), which show a different behaviour compared to the surrounding regions.

Author contribution

Gelöscht:

Gelöscht: dynamic

Gelöscht: controls

Gelöscht: and

Gelöscht: great

Gelöscht: , e.g.

Gelöscht: directly

Gelöscht: and

Gelöscht: , and sometimes even have an exactly opposite effect.

Gelöscht: wind speed at the

Gelöscht: level

[4] verschoben

Gelöscht: divided regarding

Gelöscht: realise

Gelöscht: precipitation

Gelöscht: emerged

Gelöscht: illustrates

Gelöscht: border

Gelöscht: border

Gelöscht: /region

Gelöscht:

Gelöscht: Maybe one can

Gelöscht: nevertheless

Gelöscht: but that

Gelöscht: whether

Gelöscht: development is possible or not due

Gelöscht: In a

Gelöscht: we

Gelöscht: again showed

Gelöscht: from

Gelöscht: like

Gelöscht: did

Gelöscht: maybe

Gelöscht: Liu et al., 2010; Zhang et al., 2011)

J. Curio and D. Scherer designed the study and discussed all results. J. Curio carried out the analyses and prepared the manuscript with contribution from D. Scherer.

Acknowledgements

This work was supported by the German Federal Ministry of Education and Research (BMBF) Programme “Central Asia – Monsoon Dynamics and Geo-Ecosystems” (CAME) within the WET project (“Variability and Trends in Water Balance Components of Benchmark Drainage Basins on the Tibetan Plateau”) under the code 03G0804A and by the German Research Foundation (DFG) Priority Programme 1372, “Tibetan Plateau: Formation – Climate – Ecosystems” within the DynRG-TiP (“Dynamic Response of Glaciers on the Tibetan Plateau to Climate Change”) project under the codes SCHE 750/4-1, SCHE750/4-2, SCHE 750/4-3. We would like to thank the four anonymous referees for their thoughtful comments, critiques, and suggestions on an earlier version of this manuscript.

References

Araguás-Araguás, L, and F. K, (1998). Stable isotope composition of precipitation over southeast Asia. *Journal of Geophysical Research*, *103*. Retrieved from http://onlinelibrary.wiley.com/doi/10.1029/98JD02582/full

Back, L. E., & Bretherton, C. S, (2005). The relationship between wind speed and precipitation in the Pacific ITCZ. *Journal of Climate*, *18*(20), 4317–4328. doi:10.1175/JCLI3519.1

Barros, A. P., Chiao, S., Lang, T. J., Burbank, D., & Putkonen, J. (2006). From weather to climate—Seasonal and interannual variability of storms and implications for erosion processes in the Himalaya. *Geological Society of America Special Papers*, *398*(02), 17 – 38. doi:10.1130/2006.2398(02).

Bartholy, J., & Pongracz, R. (2010). Analysis of precipitation conditions for the Carpathian Basin based on extreme indices in the 20th century and climate simulations for 2050 and 2100. *Physics and Chemistry of the Earth*, *35*(1-2), 43– 51. doi:10.1016/j.pce.2010.03.011

Bothe, O., Fraedrich, K., & Zhu, X, (2009). The large-scale circulations and summer drought and wetness on the Tibetan plateau. *International Journal of Climatology*, *855*(May 2009), n/a–n/a. doi:10.1002/joc.1946

Cannon, F., Carvalho, L. M. V., Jones, C., & Bookhagen, B, (2014). Multi-annual variations in winter westerly disturbance activity affecting the Himalaya. *Climate Dynamics*, *44*(1-2), 441–455. doi:10.1007/s00382-014-2248-8

Chen, B., Xu, X.-D., Yang, S., & Zhang, W, (2012). On the origin and destination of atmospheric moisture and air mass over the Tibetan Plateau. *Theoretical and Applied Climatology*, *110*(3), 423–435. doi:10.1007/s00704-012-0641-y

Curio, J., Maussion, F., & Scherer, D, (2015). A twelve-year high-resolution climatology of atmospheric water transport over the Tibetan Plateau. *Earth System Dynamics*, *6*, 109–124. doi:10.5194/esd-6-109-2015

Dimri, A. P., Niyogi, D., Barros, A. P., Ridley, J., Mohanty, U. C., Yasunari, T., & Sikka, D. R. (2015). Western Disturbances: A review. doi:10.1002/2014RG000460

Findell, K. L. (2003). Atmospheric controls on soil moisture-boundary layer interactions: Three-dimensional wind effects. *Journal of Geophysical Research*, *108*, 1–21.

Gelöscht:

Gelöscht: ., Froehlich,

Gelöscht: ., Rozanski, K.:

Gelöscht: J. Geophys. Res.,

Formatiert: Schriftart:Kursiv

Gelöscht: , 28721–28742,

Gelöscht: :

Gelöscht: , 1998.

Gelöscht: and

Gelöscht: .:

Formatiert: Schriftart:Kursiv

Formatiert: Schriftart:Kursiv

Gelöscht: , 2005.

Formatiert: Einzug: Links: 0 cm, Hängend: 0,75 cm

Gelöscht: and

Gelöscht: .:

Formatiert: Schriftart:Kursiv

Gelöscht: 30, 844–

Formatiert: Schriftart:Kursiv

Gelöscht: ,

Gelöscht: , 2009.

Gelöscht: and

Gelöscht: .:

Formatiert: Schriftart:Kursiv

Formatiert: Schriftart:Kursiv

Gelöscht: , 2014.

Gelöscht: and

Gelöscht: .:

Formatiert: Schriftart:Kursiv

Formatiert: Schriftart:Kursiv

Gelöscht: , 2012.

Gelöscht: .:

Formatiert: Schriftart:Kursiv

Formatiert: Schriftart:Kursiv

Gelöscht: , 2015.

doi:10.1029/2001JD001515

Forsythe, N., Blenkinsop, S., & Fowler, H. J. . (2015). Exploring objective climate classification for the Himalayan arc and adjacent regions using gridded data sources. *Earth System Dynamics*, *6*(1), 311–326. doi:10.5194/esd-6-311-2015

Frei, C., Schär, C., Lüthi, D., & Davies, H. C. (1998). Heavy precipitation processes in a warmer climate. *Geophysical Research Letters*, *25*(9), 1431. doi:10.1029/98GL51099

Garreaud, R. D. (2007). Precipitation and circulation covariability in the extratropics. *Journal of Climate*, *20*(18), 4789–4797. doi:10.1175/JCLI4257.1

Giovannettone, J. P., & Barros, A. P. (2009). Probing Regional Orographic Controls of Precipitation and Cloudiness in the Central Andes Using Satellite Data. *Journal of Hydrometeorology*, *10*(1), 167–182. doi:10.1175/2008JHM973.1

Hahn, D., & Manabe, S. (1975). The role of mountains in the south Asian monsoon circulation. *Journal of the Atmospheric Sciences*, 32, 1515-1541.

Hewitt, K. (2005). The Karakoram anomaly? Glacier expansion and the'elevation effect,'Karakoram Himalaya. *Mountain Research and Development*, *25*(4), 332–340, doi: 10.1659/0276-4741(2005)025[0332:TKAGEA]2.0.CO;2

Hren, M. T., Bookhagen, B., Blisniuk, P. M., Booth, A. L., & Chamberlain, C. P. (2009). δ18O and δD of streamwaters across the Himalaya and Tibetan Plateau: Implications for moisture sources and paleoelevation reconstructions. *Earth and Planetary Science Letters*, *288*(1-2), 20–32. doi:10.1016/j.epsl.2009.08.041

Johansson, B., & Chen, D. (2003). The influence of wind and topography on precipitation distribution in Sweden: Statistical analysis and modelling. *International Journal of Climatology*. doi:10.1002/joc.951

Joswiak, D. R., Yao, T., Wu, G., Tian, L., & Xu, B. (2013). Ice-core evidence of westerly and monsoon moisture contributions in the central Tibetan Plateau. *Journal of Glaciology*, *59*(213), 56–66. doi:10.3189/2013JoG12J035

Kurita, N., & Yamada, H. (2008). The Role of Local Moisture Recycling Evaluated Using Stable Isotope Data from over the Middle of the Tibetan Plateau during the Monsoon Season. *Journal of Hydrometeorology*, *9*(4), 760–775. doi:10.1175/2007JHM945.1

Liu, B., Xu, M., & Henderson, M. (2011). Where have all the showers gone? Regional declines in light precipitation events in China, 1960-2000. *International Journal of Climatology*, *31*(8), 1177–1191. doi:10.1002/joc.2144

Liu, J., Kang, S., Gong, T., & Lu, a. (2010). Growth of a high-elevation large inland lake, associated with climate change and permafrost degradation in Tibet. *Hydrology and Earth System Sciences*, *14*(3), 481–489. doi:10.5194/hess-14-481-2010

Liu, W., Wang, L., Chen, D., Tu, K., Ruan, C., & Hu, Z. (2015). Large-scale circulation classification and its links to observed precipitation in the eastern and central Tibetan Plateau. *Climate Dynamics*, (AUGUST). doi:10.1007/s00382-015-2782-z

Liu, X., & Yin, Z.-Y. (2001). Spatial and Temporal Variation of Summer Precipitation over the Eastern Tibetan Plateau and the North Atlantic Oscillation. *Journal of Climate*, *14*(13), 2896–2909. doi:10.1175/1520-0442(2001)014<2896:SATVOS>2.0.CO;2

Maussion, F., Scherer, D., Finkelnburg, R., Richters, J., Yang, W., & Yao, T. (2011). WRF simulation of a precipitation event over the Tibetan Plateau, China – an assessment using remote sensing and ground observations. *Hydrology and Earth System Sciences*, *15*(6), 1795–1817. doi:10.5194/hess-15-1795-2011

Gelöscht: and… Fowler, H. J.: ... [33]
Formatiert ... [34]
Gelöscht: , 2015.
Formatiert ... [35]
Gelöscht: .:
Formatiert ... [36]
Gelöscht: , 2007.
Gelöscht: Gentine,
Formatiert ... [42]
Formatiert ... [37]
Formatiert ... [38]
Gelöscht: Holtslag
Formatiert ... [39]
Gelöscht: a. M., D'Andrea, F., and Ek, M.: Surfac ... [40]
Formatiert ... [41]
Gelöscht: on the Onset
Gelöscht: Moist Convection over Land.
Formatiert ... [43]
Gelöscht: 14(5), 1443–1462.
Formatiert ... [44]
Gelöscht: JHM-D-12-0137.1, 2013.
Gelöscht: .:
Formatiert ... [45]
Gelöscht: . doi: ... [46]
Gelöscht: .:
Formatiert ... [47]
Gelöscht: http://dx.doi.org/…0.1659/0276- ... [48]
Gelöscht: and… Chamberlain, C. P.: ... [49]
Formatiert ... [50]
Gelöscht: , 2009.
Gelöscht: Janjic, Z. I.: Nonsingular Implementatio ... [51]
Gelöscht: and… Xu, B.: ... [52]
Formatiert ... [53]
Gelöscht: , 2013.
Formatiert ... [54]
Gelöscht: and… Yamada, H.: ... [55]
Formatiert ... [56]
Gelöscht: , 2008.
Formatiert ... [57]
Gelöscht: and… Lu, A.: ... [58]
Formatiert ... [59]
Gelöscht: , 2010.
Gelöscht: and… Hu, Z.: ... [60]
Formatiert ... [61]
Gelöscht: , 2015.
Gelöscht: .:
Formatiert ... [62]
Gelöscht: , 2001.
Gelöscht: Ma, Y., Wang, Y., Wu, R., Hu, Z., Yang ... [63]
Formatiert ... [64]
Gelöscht: , 2011.

Maussion, F., Scherer, D., Mölg, T., Collier, E., Curio, J., & Finkelnburg, R. (2014). Precipitation Seasonality and Variability over the Tibetan Plateau as Resolved by the High Asia Reanalysis*. *Journal of Climate*, *27*(5), 1910–1927. doi:10.1175/JCLI-D-13-00282.1

Mölg, T., & Chiang, J. (2009). Temporal precipitation variability versus altitude on a tropical high mountain: Observations and mesoscale atmospheric modelling. *Quarterly Journal of the Royal Meteorological Society*, *135*, 1439–1455. doi:10.1002/qj.461

Mölg, T., Maussion, F., & Scherer, D. (2014). Mid-latitude westerlies as a driver of glacier variability in monsoonal High Asia. *Nature Climate Change*, *4*(1), 68–73. doi:10.1038/nclimate2055

Polade, S. D., Pierce, D. W., Cayan, D. R., Gershunov, A., & Dettinger, M. D. (2014). The key role of dry days in changing regional climate and precipitation regimes. *Scientific Reports*, *4*(4364), 8pp. doi:10.1038/srep04364

Roe, G. H. (2005). Orographic Precipitation. *Annual Review of Earth and Planetary Sciences*, *33*(1), 645–671. doi:10.1146/annurev.earth.33.092203.122541

Rose, B. E. J., & Lin, C. A. (2003). Precipitation from vertical motion: A statistical diagnostic scheme. *International Journal of Climatology*, *23*(8), 903–919. doi:10.1002/joc.919

Rüthrich, F. (2015). Lake-Related Cloud Dynamics on the Tibetan Plateau: Spatial Patterns and Interannual Variability. *Journal of Climate*, *28*, 9080-910. doi: 10.1175/JCLI-D-14-00698.1

Schiemann, R., & Lüthi, D. (2008). The precipitation climate of Central Asia—intercomparison of observational and numerical data sources in a remote semiarid region. *International Journal of Climatology*, 28, 295–314. doi:10.1002/joc.1532

Schiemann, R., Lüthi, D., & Schär, C. (2009). Seasonality and Interannual Variability of the Westerly Jet in the Tibetan Plateau Region*. *Journal of Climate*, *22*(11), 2940–2957. doi:10.1175/2008JCLI2625.1

Shinker, J. J., Bartlein, P. J., & Shuman, B. (2006). Synoptic and dynamic climate controls of North American mid-continental aridity. *Quaternary Science Reviews*, *25*(13-14), 1401–1417. doi:10.1016/j.quascirev.2005.12.012

Skamarock, W., & Klemp, J. (2008). A time-split nonhydrostatic atmospheric model for weather research and forecasting applications. *Journal of Computational Physics*, *227*(7), 3465–3485. doi:10.1016/j.jcp.2007.01.037

Spiess, M., Schneider, C., & Maussion, F. (2015). MODIS-derived interannual variability of the equilibrium-line altitude across the Tibetan Plateau. *Annals of Glaciology*, *57*(71), 140–154. doi:10.3189/2016AoG71A014

Tian, L., Yao, T., MacClune, K., White, J. W. C., Schilla, a., Vaughn, B., … Ichiyanagi, K. (2007). Stable isotopic variations in west China: A consideration of moisture sources. *Journal of Geophysical Research*, *112*(D10), D10112. doi:10.1029/2006JD007718

Trenberth, K. E. (1999). Atmospheric Moisture Recycling: Role of Advection and Local Evaporation. *Journal of Climate*, *12*(5), 1368–1381. doi:10.1175/1520-0442(1999)012<1368:AMRROA>2.0.CO;2

Webster, P., Magana, V., & Palmer, T. (1998). Monsoons: Processes, predictability, and the prospects for prediction. *Journal of Geophysical Research*, *103* (C7), 14451-14510.

Xu, X., Lu, C., Shi, X., & Gao, S. (2008). World water tower: An atmospheric perspective. *Geophysical Research Letters*, 35, L20815, doi: 10.1029/2008GL035867

Yang, K., Wu, H., Qin, J., Lin, C., Tang, W., & Chen, Y. (2014). Recent climate changes over

Gelöscht: .:

Gelöscht: , 2014.

Formatiert: Schriftart:Kursiv

Gelöscht: Medeiros, B., Hall, A., & Stevens, B.: What controls the mean depth of the PBL? Journal of Climate, 18(16), 3157–3172. doi:10.1175/JCLI3417.1, 2005. ... [65]

Formatiert: Schriftart:Kursiv

Gelöscht: , 1439–1455… doi:10.1002/qj, 2009. ... [66]

Gelöscht: and… Scherer, D.: ... [67]

Formatiert: Schriftart:Kursiv

Gelöscht: , 2013.

Gelöscht: Patil, M. N., Patil, S. D., Waghmare, R. T., & Dharmaraj, T.: Planetary Boundary Layer height over the Indian subcontinent during extreme monsoon years. *Journal of Atmospheric and Solar-Terrestrial Physics*, *92*, 94–99. doi:10.1016/j.jastp.2012.10.011, 2013.

Formatiert: Blocksatz, Abstand Vor: 5 Pt.

Gelöscht: ., Reudenbach, C., Thies, B., and Bendix, J.:… (2015). Lake-Related Cloud Dynamics on the Tibetan Plateau: Spatial Patterns and Interannual Variability. ... [68]

Formatiert ... [69]

Gelöscht: –9104.doi: http://dx.doi.org/10.1175/JCLI-D-14-00698.1, 2015.

Gelöscht: and… Lüthi, D.:… (2008). The precipitation climate of Central Asia—intercomparison of observ ... [70]

Gelöscht: and… Schär, C.: ... [71]

Formatiert ... [72]

Gelöscht: , 2009.

Gelöscht: and… Shuman, B.: ... [73]

Formatiert ... [74]

Gelöscht: , 2006.

Gelöscht: and… Klemp, J.: ... [75]

Formatiert: Schriftart:Kursiv

Gelöscht: , 2008.

Gelöscht: and… Maussion, F.:. ... [76]

Formatiert ... [77]

Gelöscht: , 2015.

Gelöscht: A

Formatiert: Schriftart:Times New Roman

Gelöscht: Vachon, R., and… Ichiyanagi, K.: ... [78]

Gelöscht: ,… doi:10.1029/2006JD007718, 2007. ... [80]

Formatiert ... [79]

Gelöscht: .:

Formatiert ... [81]

Gelöscht: , 1999.

Gelöscht: N., Shukla, J., Tomas, R. A., Yanai, M., ... [82]

Formatiert: Schriftart:Kursiv

Gelöscht: ,…*(C7)*, 14451-14510, doi:10.1029/97J ... [83]

Gelöscht: Wilks, D. S.: Statistical Methods in the ... [84]

Gelöscht: Yang, K., Koike, T., Fujii, H., Tamura, ... [85]

the Tibetan Plateau and their impacts on energy and water cycle: A review. *Global and Planetary Change*, *112*, 79–91. doi:10.1016/j.gloplacha.2013.12.001

Zhang, J. W., & Atkinson, B. W. (1995). Stability and wind shear effects on meso-scale cellular convection. *Boundary-Layer Meteorology*, *75*(3), 263–285. doi:10.1007/BF00712697

Zhang, G., Xie, H., Kang, S., Yi, D., & Ackley, S. F. (2011). Monitoring lake level changes on the Tibetan Plateau using ICESat altimetry data (2003-2009). *Remote Sensing of Environment*, *115*(7), 1733–1742. doi:10.1016/j.rse.2011.03.005

Formatiert: Schriftart:Kursiv

Gelöscht: , 2014.

Formatiert: Schriftart:Kursiv

Gelöscht: and

Gelöscht: .:

Formatiert: Schriftart:Kursiv

Gelöscht: , 2011.

Formatiert: Schriftart:Kursiv

Formatiert: Blocksatz

Gelöscht: ... [86]

Figures

Formatiert: Blocksatz

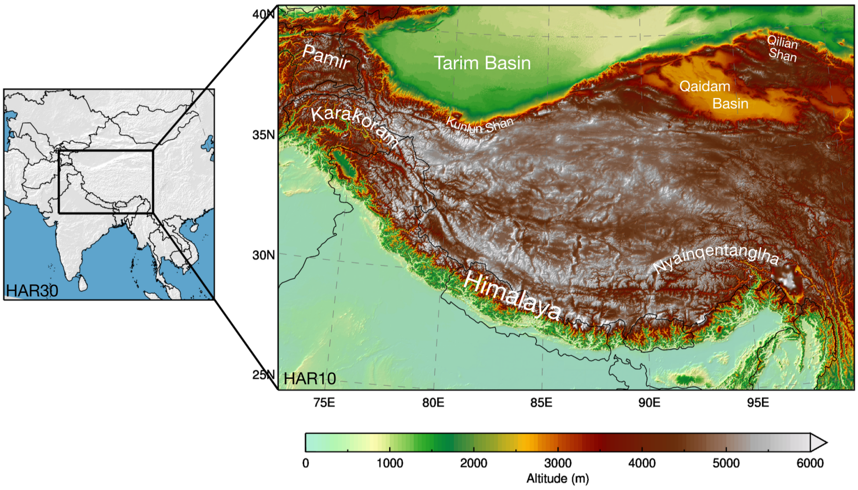
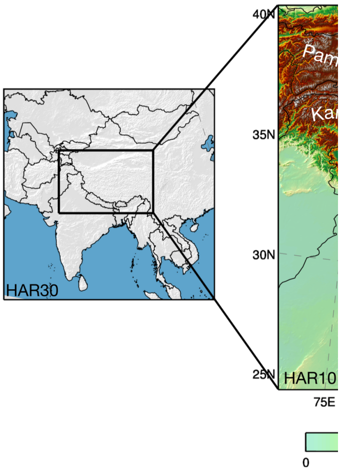


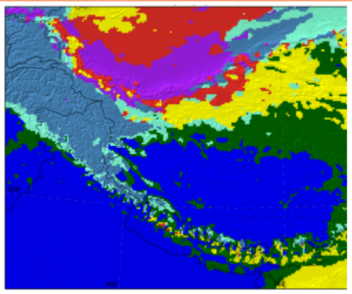
Fig. 1: Map of the Weather and Research Forecasting (WRF) model domain HAR10 (high Asia domain) and its location nested in the larger domain HAR30 (south-central Asia domain). Geographical locations are indicated in white.

Gelöscht:



Formatiert: Standard, Blocksatz

Gelöscht:



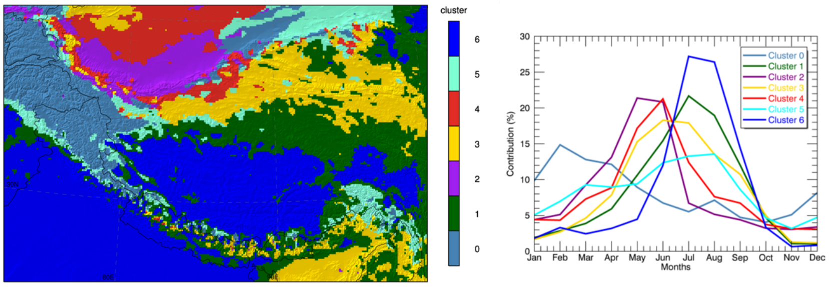


Fig. 2: Precipitation cluster (left) and the mean annual cycle of percentage contribution of monthly precipitation to annual precipitation for each cluster (right).

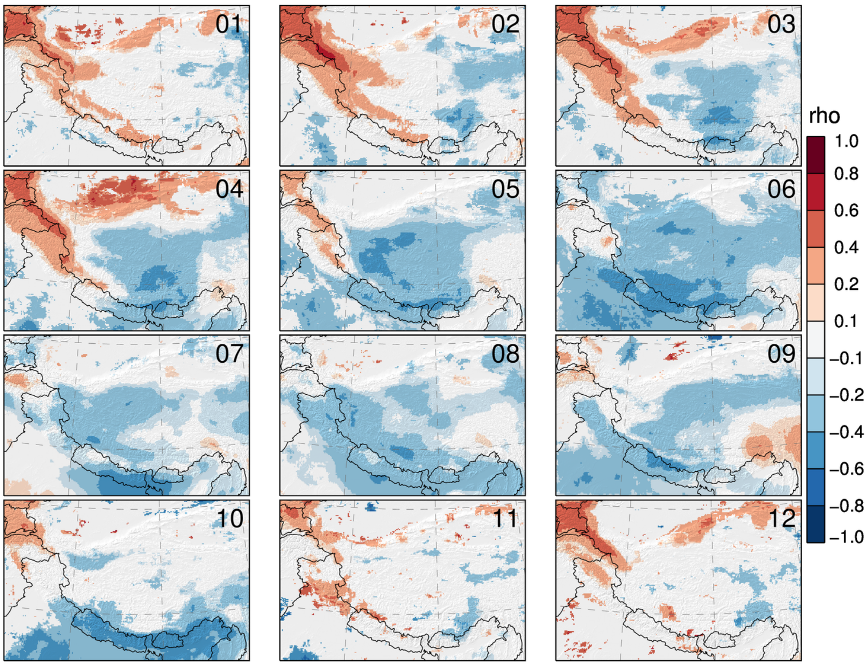


Figure 3. Coefficient of correlation (rho) between horizontal wind speed at 300 hPa (WS300) and precipitation for all months (01-12). Positive correlations are denoted in red, while negative correlations are denoted in blue.

Gelöscht: ... [87]

Gelöscht: :

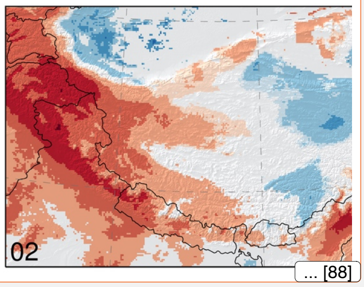
Formatiert: Deutsch

Formatiert: Schriftart:+Designkörper (Calibri), Deutsch

Formatiert: Standard, Blocksatz

Gelöscht: February (02), April (04), and June (06).

Formatiert: Schriftart:+Designkörper (Calibri), Deutsch



Gelöscht: ... [88]

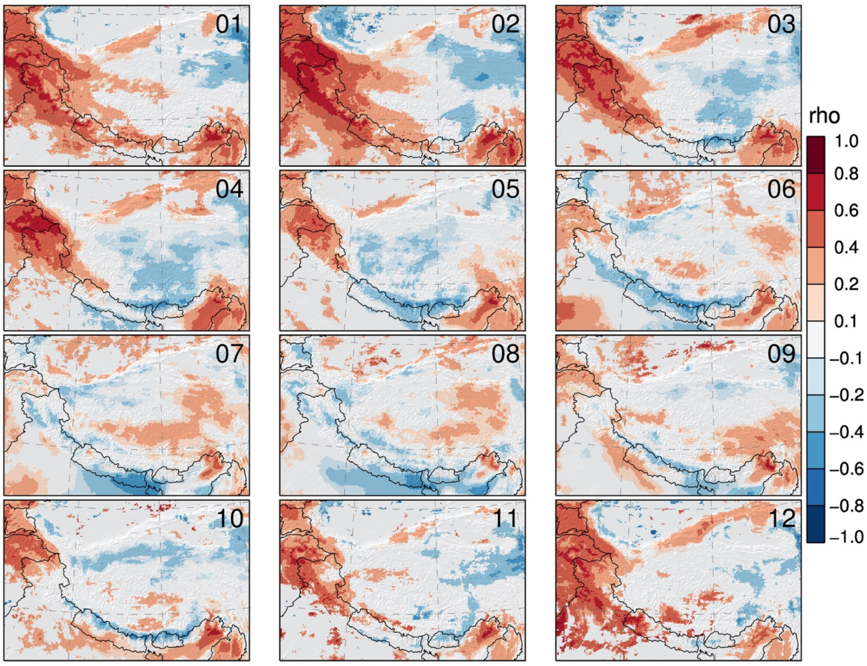


Figure 4. Coefficient of correlation (rho) between horizontal wind speed at model level 10 (WS10) and precipitation for all months (01-12). Positive correlations are denoted in red, while negative correlations are denoted in blue.

Formatiert: Deutsch

Formatiert: Standard, Blocksatz

Gelöscht: :

Formatiert: Schriftart:+Designkörper (Calibri), Deutsch

Gelöscht: February (02) and July (07). Positive correlations are denoted in red, while negative correlations are denoted in blue.

... [89]

Formatiert: Schriftart:+Designkörper (Calibri), Deutsch

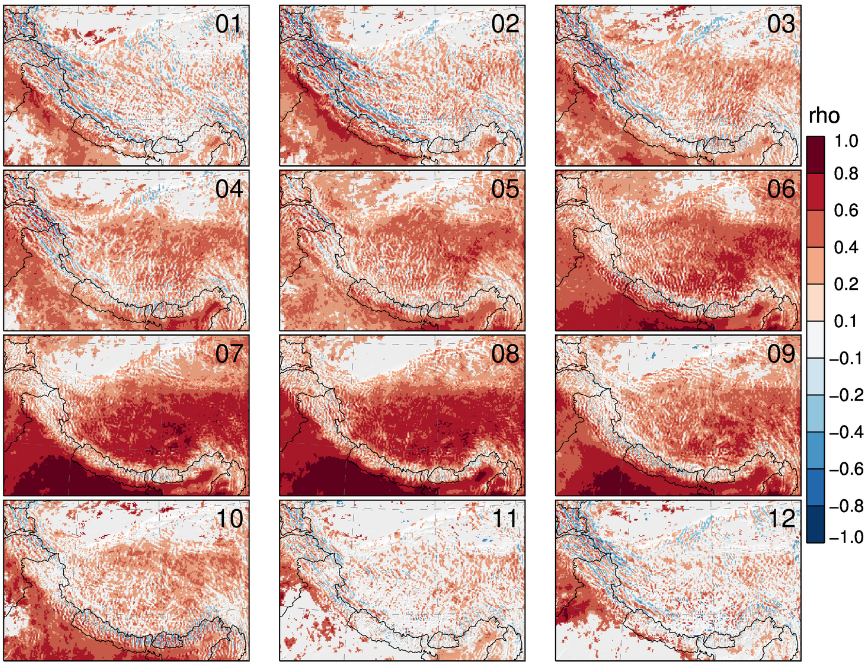
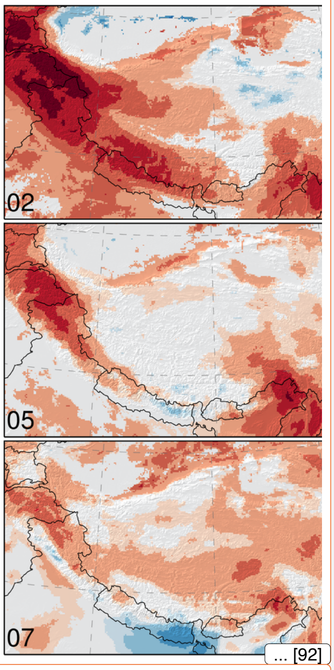


Figure 5. Coefficient of correlation (rho) between vertical wind speed at 300 hPa (WS300) and precipitation for all months (01-12). Positive correlations are denoted in red, while negative correlations are denoted in blue.

Gelöscht: ... [90]

[6] nach unten: Fig. 6: Mean vertical wind speed at 300 hPa for January (01) and July (07). ... [91]



Gelöscht: ... [92]

Formatiert: Standard, Blocksatz

Formatiert: Schriftart:+Designkörper (Calibri), Deutsch

Gelöscht: column integrated atmospheric water transport (AWT

Gelöscht: February (02), May (05), and July (07

Formatiert: Schriftart:+Designkörper (Calibri), Deutsch

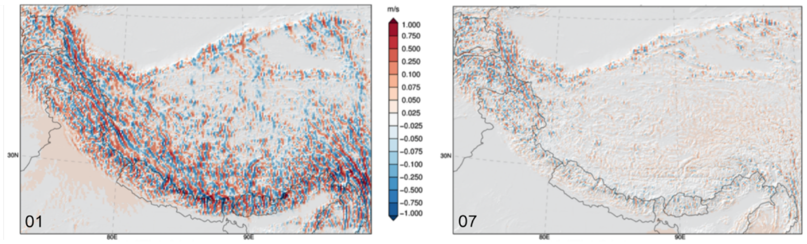


Fig. 6: Mean vertical wind speed at 300 hPa for January (01) and July (07).

[6] verschoben

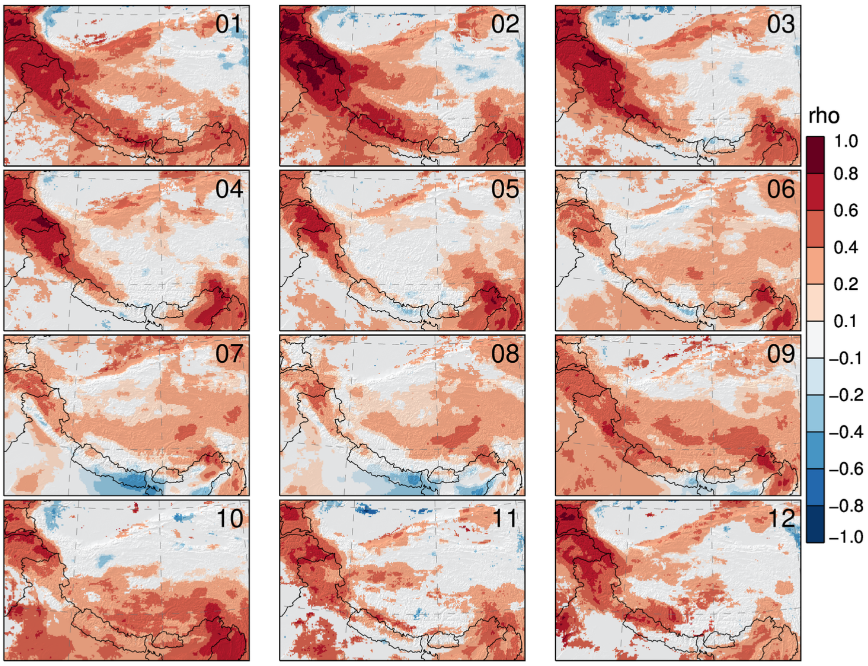
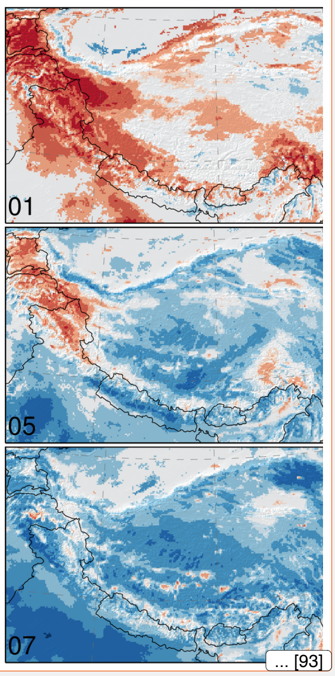


Figure 7. Coefficient of correlation (rho) between atmospheric water transport (AWT) and precipitation for all months (01-12). Positive correlations are denoted in red, while negative correlations are denoted in blue.

Gelöscht:



... [93]

Gelöscht: planetary boundary layer height (PBLH

Formatiert: Standard, Blocksatz

Formatiert: Schriftart:+Designkörper (Calibri), Deutsch

Gelöscht: January

Gelöscht:), May (05), and July (07

Formatiert: Schriftart:+Designkörper (Calibri), Deutsch

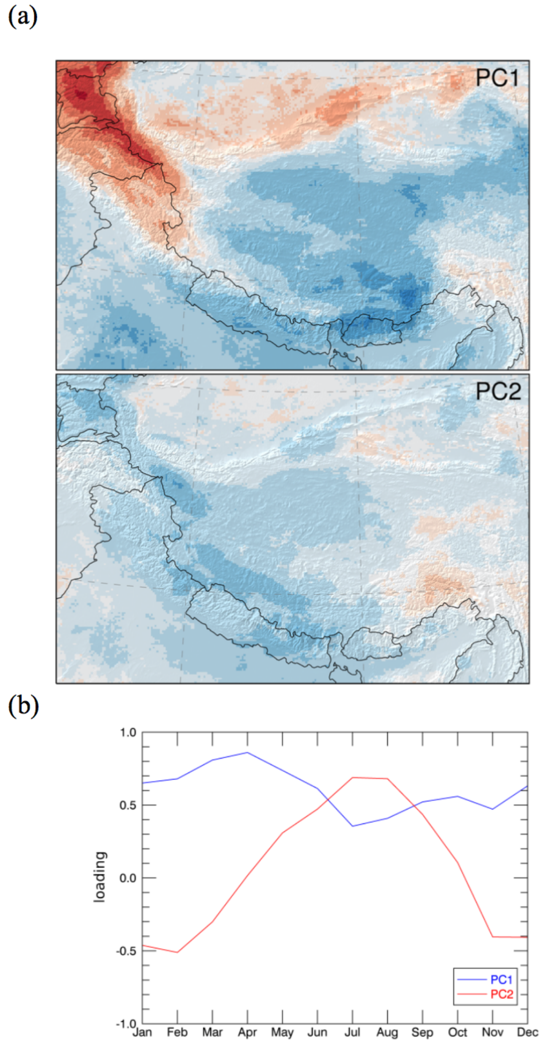
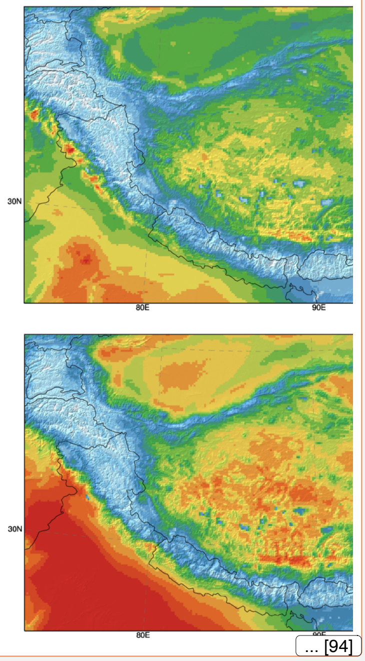


Figure 8. Scores of first two principal components PC1 and PC2 for the correlation between horizontal wind speed at 300 hPa (WS300) and precipitation **(a)** (positive values are denoted in red, while negative values are denoted in blue) and the monthly loadings **(b)** for both PCs.



Gelöscht: ... [94]

Gelöscht: 10

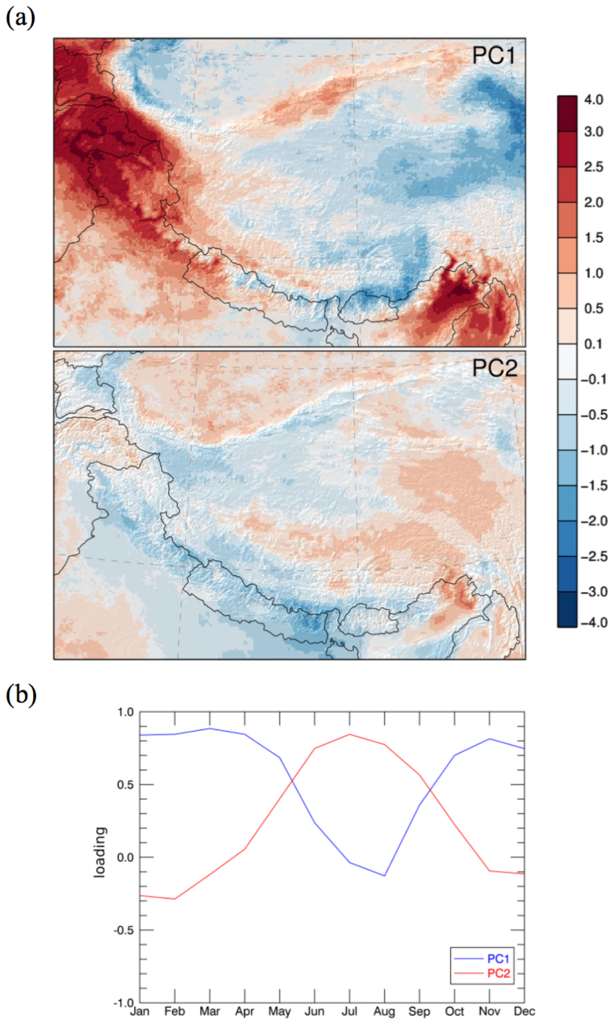


Figure 9. Scores of first two principal components PC1 and PC2 for the correlation between horizontal wind speed at model level 10 (WS10) and precipitation **(a)** (positive values are denoted in red, while negative values are denoted in blue) and the monthly loadings **(b)** for both PCs.

Gelöscht: ... [95]

Gelöscht: 11

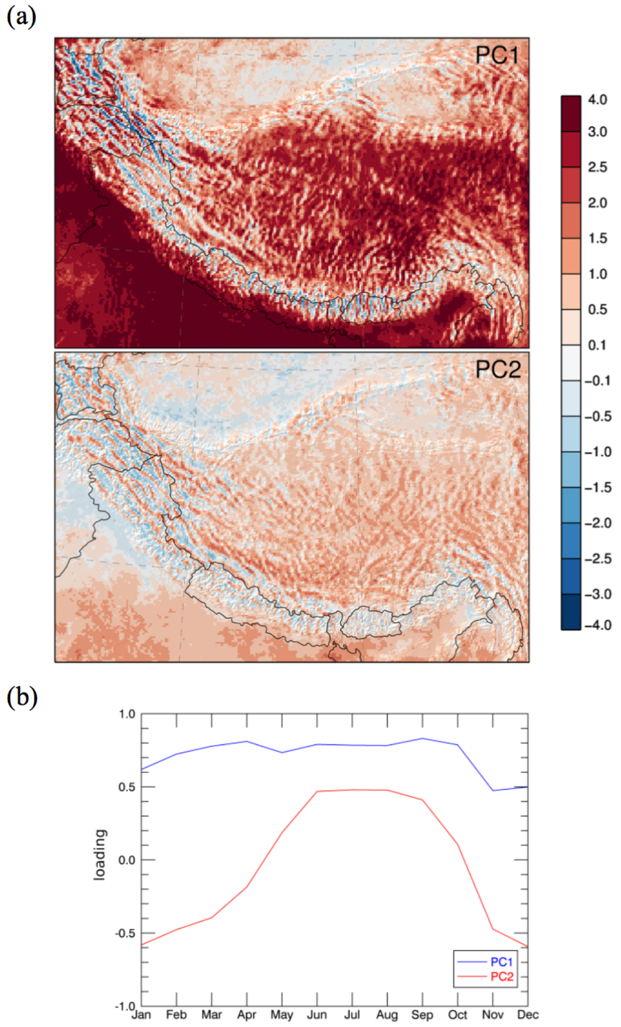
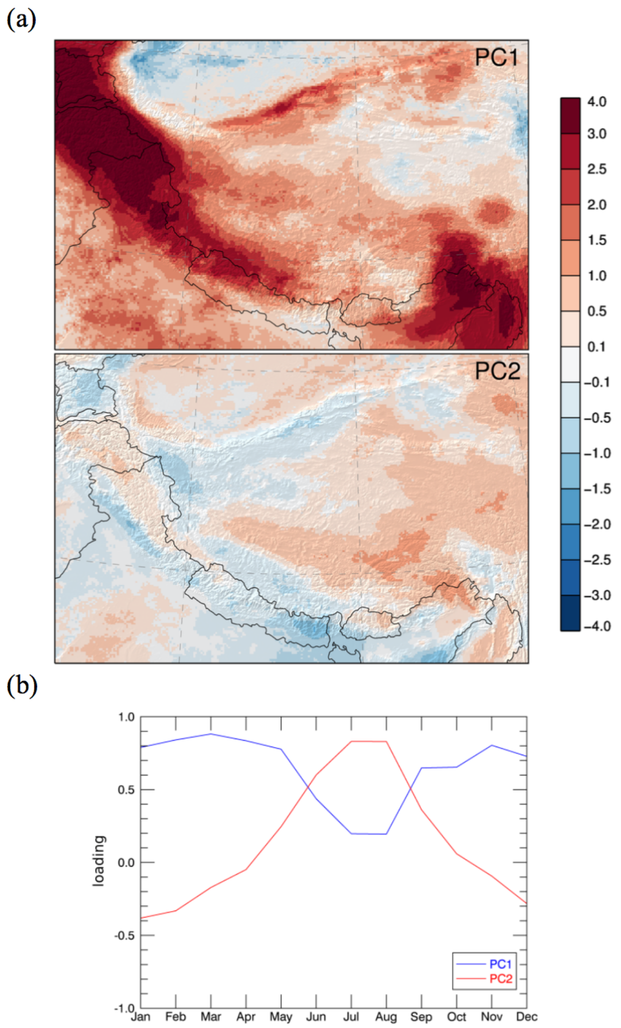


Figure 10. Scores of first two principal components PC1 and PC2 for the correlation between vertical wind speed at 300 hPa (W300) and precipitation **(a)** (positive values are denoted in red, while negative values are denoted in blue) and the monthly loadings **(b)** for both PCs.

Gelöscht: ... [96]

Gelöscht: 12

Formatiert: Schriftart:Times New Roman, 12 pt



Gelöscht: ... [97]

Figure 11. Scores of first two principal components PC1 and PC2 for the correlation between atmospheric water transport (AWT) and precipitation **(a)** (positive values are denoted in red, while negative values are denoted in blue) and the monthly loadings **(b)** for both PCs.

Gelöscht: 13

Gelöscht: ... [98]

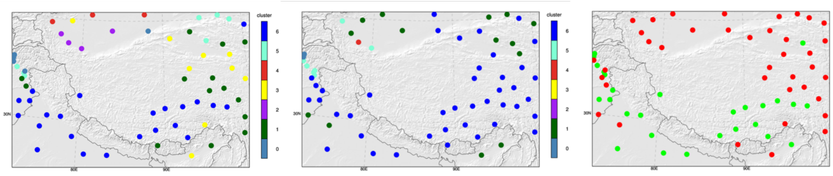


Figure 12. Map of precipitation cluster for HAR10 grid points (left) and the associated NCDC stations (middle). The map on the right shows whether the cluster match (green dots) or not (red dots).

Tables

cluster		NCDC						
		0	1	2	3	4	5	6
HAR	0	40 %	0 %	0 %	0 %	0 %	40 %	20 %
	1	0 %	14.3 %	0 %	0 %	0 %	0 %	85.7 %
	2	0 %	50 %	0 %	0 %	25 %	25 %	0 %
	3	0 %	33.3 %	0 %	0 %	0 %	0 %	66.6 %
	4	0 %	33.3 %	0 %	0 %	0 %	33.3 %	33.3 %
	5	0 %	43 %	0 %	0 %	0 %	43 %	14 %
	6	0 %	13 %	0 %	0 %	0 %	0 %	87 %

Table 1. The percentage of NCDC stations falling in each of the seven possible HAR cluster. 100% would mean that all NCDC stations falls in the same cluster as the nearest HAR grid point.

Seite 1: [1] Gelöscht **Julia Curio** **01.08.16 23:13**

There are many studies on the influence of atmospheric circulation modes, e.g. the North Atlantic Oscillation, the Arctic Oscillation, and El Nino/Southern Oscillation, on climate and precipitation in high Asia and on the monsoon systems (e.g. Bothe et al., 2009; Liu et al., 2015; Liu and Yin, 2001; Rüthrich et al., 2015). Less attention is drawn to the underlying processes controlling precipitation development on the TP and the surrounding high mountain ranges.
Using the

Seite 2: [2] Formatiert **Julia Curio** **01.08.16 23:13**

Abstand Vor: 0 Pt., Abstand zwischen Absätzen gleicher Formatierung einfügen, Keine Absatzkontrolle, Leerraum zwischen asiatischem und westlichem Text nicht anpassen, Leerraum zwischen asiatischem Text und Zahlen nicht anpassen

Seite 2: [3] Gelöscht **Julia Curio** **01.08.16 23:13**

Therefore, we want to examine which precipitation controls has where and when an

Seite 2: [4] Auf Seite 4 verschoben (Verschiebung Nr. 2) **Julia Curio**
01.08.16 23:13

The selection of precipitation controls relies on well studied relations of these factors with precipitation (e.g.

Seite 2: [5] Gelöscht **Julia Curio** **01.08.16 23:13**

Back and Bretherton, 2005; Garreaud, 2007; Shinker et al., 2006) but these controls were not investigated at high spatial and temporal resolution in high mountain Asia until now.

Seite 2: [6] Auf Seite 2 verschoben (Verschiebung Nr. 1) **Julia Curio**
01.08.16 23:13

The different precipitation controls have effects on different spatial scales.

Seite 2: [7] Gelöscht **Julia Curio** **01.08.16 23:13**

While the horizontal and vertical wind speed at 300 hPa are large-scale controls, their counter parts in the boundary layer and the PBLH are active on the meso-scale. The AWT connects the large- with the meso-scale because it is effective on both scales and across large distances.

Seite 2: [8] Kommentiert **Ein Microsoft Office-Anwender** **27.07.16 16:28**

Since the precipitation distribution on the Tibetan Plateau is influenced by both the Indian Summer Monsoon and the mid-latitude westerlies (e.g. Maussion et al., 2014; Böhner et al., 2006), we focus on dynamic precipitation controls which are related to these two atmospheric circulation features. We have to make more clear that the focus of the study is not to examine precipitation development but the reasons for precipitation variability. We apologize that the former use of the phrase precipitation development was misleading the reader. This variability is influenced by the atmospheric circulation and the related variables like horizontal and vertical wind and moisture transport. We choose variables from the HAR data set, which are already proven to be in good agreement with observations and gridded datasets. The selected controls are well known to have an impact on precipitation variability. The positive effect of AWT on precipitation variability is described in, for example, Barros et al. (2006), Giovannetone et al. (2009) and Zhou et al. (2005). The positive effect of higher wind speeds on moisture advection and orographic lifting, and in lower levels enhancing evaporation and therefore their positive correlations with precipitation are known in the literature (e.g. Johansson and Chen (2003), McVicar (2012), Roe (2005)). Higher wind speeds in higher atmospheric levels can cut of deep convection via the wind shear effect, studies showing this effect are, for example, Findell et al. (2003) and Zhang and Atkinson (1995). Rose et al. (2003) show effects of vertical wind speed and most important its direction on precipitation. Updrafts lead to an increase of precipitation while downdrafts lead to a decrease of precipitation. Of course there are other variables influencing precipitation, but we think that our selection is suitable for our study region.

Seite 2: [9] Gelöscht	**Julia Curio**	**01.08.16 23:13**

with low horizontal wind speeds. On the other hand, high wind speeds enhance moisture advection and thereby strengthen frontal/cyclonic precipitation and also orographic precipitation. At the 300 hPa level we are already in a height where the westerly jet occurs, which strength and location influences the hydro-climate of the TP and central Asia (e.g. Schiemann et al., 2009).

Seite 2: [10] Formatiert	**Julia Curio**	**01.08.16 23:13**

Abstand Vor: 0 Pt., Abstand zwischen Absätzen gleicher Formatierung einfügen, Keine Absatzkontrolle, Leerraum zwischen asiatischem und westlichem Text nicht anpassen, Leerraum zwischen asiatischem Text und Zahlen nicht anpassen

Seite 2: [11] Gelöscht	**Julia Curio**	**01.08.16 23:13**

Higher horizontal wind speeds in the planetary boundary layer can hinder convection and advect air masses/moisture like its counterpart at 300 hPa, but also can enhance evapotranspiration from the surface (Back & Bretherton, 2005) and therefore convection, depending on the available moisture at the surface. This process is interesting mostly during the warm half of the year, when surface moisture from local sources like lakes, soil moisture, the active layer of permafrost, snow and glacier melt is available. Moisture recycling plays an important role for precipitation on the TP (e.g. Araguás-Araguás et al., 1998; Trenberth, 1999)

Seite 2: [12] Auf Seite 2 verschoben (Verschiebung Nr. 3) **Julia Curio** **01.08.16 23:13**

, on average more than 60% of moisture needed for precipitation falling on the inner TP are provided by the TP itself (Curio et al., 2015).

Seite 2: [13] Gelöscht **Julia Curio** **01.08.16 23:13**

Back and Bretherton (2005) found that there is a relation between near surface wind speed and precipitation in the Pacific ITCZ. Higher wind speeds can intensify the evapotranspiration rate and therefore the development of deep convection.

Seite 2: [14] Auf Seite 13 verschoben (Verschiebung Nr. 4) **Julia Curio** **01.08.16 23:13**

The negative effect of high horizontal wind speeds on precipitation plays an important role in regions and seasons which are dominated by convective precipitation e.g. the Tibetan Plateau in summer (Maussion et al. 2014).

Seite 2: [15] Gelöscht **Julia Curio** **01.08.16 23:13**

While the positive effect occurs in regions with mainly frontal/cyclonic precipitation because the moisture transport towards these regions is enhanced by the strengthened atmospheric flow.

Seite 3: [16] Gelöscht **Julia Curio** **01.08.16 23:13**

The height of the planetary boundary layer (PBLH) shows the turbulent mixing of the lower atmosphere. It is influenced by solar forcing, turbulent processes, convective activity (Yang et al., 2004), moisture content and temperature of surface and air, and wind speed. Gentine et al. (2013) point out that dry soil surface accelerates the growth of the PBL. The TP has one of the highest PBLs in the world, due to its high altitude and strong solar forcing, but the TP PBL is not fully understood yet because there are only few observations. During daytime in spring and summer the PBL is higher than in the other seasons in this region (Patil et al., 2013) and can exceed heights of 3000 m or more (Ma et al., 2009; Yang et al., 2004) in some regions on the TP due to strong solar forcing and convective activity. The horizontal wind speed influences the PBLH by facilitating the mixing of the atmosphere and the entrainment of air from above the PBL. The PBLH is not a pure dynamic precipitation control, but entrainment as a dynamic factor has great impact on PBLH (Medeiros et al., 2005; Gentine et al., 2013). Additionally, in the HAR the PBLH is determined dynamically by using the Mellor–Yamada–Janjic turbulent kinetic energy scheme (Janjic, 2002) for PBL parameterisation.

The objectives of the current study are two-fold:
i.

Seite 3: [17] Formatiert **Julia Curio** **01.08.16 23:13**

Einzug: Links: 0 cm, Erste Zeile: 0 cm, Abstand Vor: 0 Pt., Nach: 6 Pt., Keine Absatzkontrolle, Leerraum zwischen asiatischem und westlichem Text nicht anpassen, Leerraum zwischen asiatischem Text und Zahlen nicht anpassen

Seite 3: [18] Gelöscht **Julia Curio** **01.08.16 23:13**

controls on precipitation development spatially and temporally differentiated, where and when has which precipitation control a how strong influence,

Seite 3: [19] Formatiert **Julia Curio** **01.08.16 23:13**

Schriftart:Times, Schriftfarbe: Text 1, Deutsch

Seite 3: [20] Gelöscht **Julia Curio** **01.08.16 23:13**

if precipitation controls have always and everywhere in the study region the same impact or

Seite 4: [21] Gelöscht **Julia Curio** **01.08.16 23:13**

2.2. Methods
For the analyses in this study we selected the years 2001-2013 as study period and use daily HAR data. The data set is then stratified, because we are only interested in precipitation days, this is done month-wise. For example, all July analysis depend on the data basis of each July day during 2001-2013, these are 31*13 days, total 403 days. Therefor all analyses are conducted for precipitation days only. Precipitation days for a grid point are defined as days with a mean daily precipitation rate of 0.1 mm. This value

Seite 5: [22] Gelöscht **Julia Curio** **01.08.16 23:13**

, with a level of significance of 0.05, are plotted. Following this, a principal component analysis (PCA) was performed for the correlations between controls and precipitation to detect the dominant patterns.
Due to the use of correlations we avoid

Seite 5: [23] Gelöscht **Julia Curio** **01.08.16 23:13**

(green). This class represents a transition zone where the monsoon can have influence but is not dominant.

Seite 5: [24] Formatiert **Julia Curio** **01.08.16 23:13**

Abstand Vor: 0 Pt., Keine Absatzkontrolle, Leerraum zwischen asiatischem und westlichem Text nicht anpassen, Leerraum zwischen asiatischem Text und Zahlen nicht anpassen

Seite 6: [25] Gelöscht **Julia Curio** **01.08.16 23:13**

We only show the months with the most prominent features. Figures with the correlation of each dynamic control with precipitation for all months are provided in the supplemental material for completeness.

Seite 8: [26] Formatiert **Julia Curio** **01.08.16 23:13**

Schriftfarbe: Text 1

Seite 8: [26] Formatiert **Julia Curio** **01.08.16 23:13**

Schriftfarbe: Text 1

Seite 8: [27] Formatiert **Julia Curio** **01.08.16 23:13**

Schriftfarbe: Text 1

Seite 8: [27] Formatiert **Julia Curio** **01.08.16 23:13**

Schriftfarbe: Text 1

Seite 8: [28] Gelöscht Julia Curio 01.08.16 23:13

provides

Seite 8: [28] Gelöscht Julia Curio 01.08.16 23:13

provides

Seite 8: [28] Gelöscht Julia Curio 01.08.16 23:13

provides

Seite 8: [28] Gelöscht Julia Curio 01.08.16 23:13

provides

Seite 8: [28] Gelöscht Julia Curio 01.08.16 23:13

provides

Seite 8: [28] Gelöscht Julia Curio 01.08.16 23:13

provides

Seite 8: [28] Gelöscht Julia Curio 01.08.16 23:13

provides

Seite 8: [28] Gelöscht Julia Curio 01.08.16 23:13

provides

Seite 8: [28] Gelöscht Julia Curio 01.08.16 23:13

provides

Seite 8: [28] Gelöscht Julia Curio 01.08.16 23:13

provides

Seite 8: [28] Gelöscht Julia Curio 01.08.16 23:13

provides

Seite 8: [29] Gelöscht **Julia Curio** **01.08.16 23:13**

,

Seite 8: [29] Gelöscht **Julia Curio** **01.08.16 23:13**

,

Seite 8: [29] Gelöscht **Julia Curio** **01.08.16 23:13**

,

Seite 8: [29] Gelöscht **Julia Curio** **01.08.16 23:13**

,

Seite 8: [29] Gelöscht **Julia Curio** **01.08.16 23:13**

,

Seite 8: [30] Gelöscht **Julia Curio** **01.08.16 23:13**

now we have

Seite 8: [30] Gelöscht **Julia Curio** **01.08.16 23:13**

now we have

Seite 8: [30] Gelöscht **Julia Curio** **01.08.16 23:13**

now we have

Seite 9: [31] Gelöscht **Julia Curio** **01.08.16 23:13**

3.2.4 Planetary boundary layer height (PBLH)

In Winter the correlation between PBLH and precipitation (Fig. 8) are mainly positive, especially in the PKwH Himalaya region, forming a coherent pattern, and along the northern and southern border of the TP, with some interruptions, and in the eastern TP around the Brahmaputra Channel. PBLH is a precipitation control which is itself controlled by horizontal wind speed, among others. The positive correlations in winter in the Pamir/Karakoram region can be explained by higher horizontal wind speeds and thereby more moisture advection leading to more precipitation, like described earlier. Higher horizontal wind speeds lead to higher entrainment rates at the top of the PBL whereby the depth of the PBL increases.
During the year this picture changes and negative correlations become dominant. The negative correlations occur in regions and seasons dominated by convection and consequently

convective precipitation. Higher PBLH are caused by higher horizontal wind speeds which have a negative effect on precipitation by cutting off deep convection, as previously pointed out in this study. In May we see positive correlations left only in the centre of the Pamir/Karakoram region and in the eastern TP, while in summer just small and scattered areas with positive correlations occur. Most of these areas on the central TP match with the large lakes, e.g. Nam Co, Serling Co, and Tangra Yumco.

To understand these contrary correlations, compared with the direct surroundings of the lakes, we have to look at the PBLH itself. Figure 9 shows the averaged daily mean and daily maximum PBLH for May as an example. The lowest PBLHs (mean and maximum) in the domain are found at the high mountain ranges bordering the TP, because of the high altitudes and low temperatures, and above the large lakes on the central TP. Reason for this seems to be the fact that during daytime when the air temperature above land is higher than above the lakes, the air above the land starts to ascend and there is strong convective activity which is amplified at the slopes of the surrounding mountain ranges (due to higher solar insulation). Recirculation of the ascended air leads to subsidence of air above the lakes which lowers the PBLH and supresses precipitation. Suppression of precipitation by subsidence was already described in Curio et al. (2015) for larger regions like the Qaidam Basin and the north-western parts of India and Pakistan.

The positive correlations above the lakes, mean that higher PBLH leads to more precipitation in this area. These higher PBLH occur when the wind speeds are higher, which leads to more entrainment, which causes a deepening of the PBL above the lakes. This effect slightly equalizes the PBLHs above the lakes and the surrounding land and the differences become smaller. Due to the increase of the PBLH, the prevailing subsidence above the lakes weakens and precipitation development becomes possible.

Seite 11: [32] Gelöscht Julia Curio 01.08.16 23:13

Seite 15: [33] Gelöscht Julia Curio 01.08.16 23:13

and

Seite 15: [33] Gelöscht Julia Curio 01.08.16 23:13

and

Seite 15: [34] Formatiert Julia Curio 01.08.16 23:13

Schriftart:Kursiv

Seite 15: [34] Formatiert Julia Curio 01.08.16 23:13

Schriftart:Kursiv

Seite 15: [35] Formatiert Julia Curio 01.08.16 23:13

Einzug: Links: 0 cm, Hängend: 0,85 cm

Seite 15: [36] Formatiert Julia Curio 01.08.16 23:13

Schriftart:Kursiv

Seite 15: [36] Formatiert Julia Curio 01.08.16 23:13

Schriftart:Kursiv

Seite 15: [37] Formatiert Julia Curio 01.08.16 23:13

Einzug: Links: 0 cm, Hängend: 0,75 cm

Seite 15: [38] Formatiert Julia Curio 01.08.16 23:13

Englisch (Vereinigtes Königreich)

Seite 15: [39] Formatiert Julia Curio 01.08.16 23:13

Englisch (Vereinigtes Königreich)

Seite 15: [40] Gelöscht Julia Curio 01.08.16 23:13

a. M., D'Andrea, F., and Ek, M.: Surface and Atmospheric

Seite 15: [41] Formatiert Julia Curio 01.08.16 23:13

Englisch (Vereinigtes Königreich)

Seite 15: [42] Formatiert Julia Curio 01.08.16 23:13

Englisch (Vereinigtes Königreich)

Seite 15: [43] Formatiert Julia Curio 01.08.16 23:13

Englisch (Vereinigtes Königreich)

Seite 15: [43] Formatiert Julia Curio 01.08.16 23:13

Englisch (Vereinigtes Königreich)

Seite 15: [43] Formatiert Julia Curio 01.08.16 23:13

Englisch (Vereinigtes Königreich)

Seite 15: [44] Formatiert Julia Curio 01.08.16 23:13

Englisch (Vereinigtes Königreich)

Seite 15: [45] Formatiert Julia Curio 01.08.16 23:13

Schriftart:Kursiv

Seite 15: [46] Gelöscht Julia Curio 01.08.16 23:13

. doi: http://journals.ametsoc.org/doi/abs/10.1175/1520-0469(1975)032<

Seite 15: [46] Gelöscht Julia Curio 01.08.16 23:13

. doi: http://journals.ametsoc.org/doi/abs/10.1175/1520-0469(1975)032<

Seite 15: [47] Formatiert Julia Curio 01.08.16 23:13

Schriftart:Kursiv

Seite 15: [47] Formatiert Julia Curio 01.08.16 23:13

Schriftart:Kursiv

Seite 15: [48] Gelöscht Julia Curio 01.08.16 23:13

http://dx.doi.org/

Seite 15: [48] Gelöscht Julia Curio 01.08.16 23:13

http://dx.doi.org/

Seite 15: [49] Gelöscht Julia Curio 01.08.16 23:13

and

Seite 15: [49] Gelöscht Julia Curio 01.08.16 23:13

and

Seite 15: [50] Formatiert Julia Curio 01.08.16 23:13

Schriftart:Kursiv

Seite 15: [50] Formatiert Julia Curio 01.08.16 23:13

Schriftart:Kursiv

Seite 15: [51] Gelöscht **Julia Curio** **01.08.16 23:13**

Janjic, Z. I.: Nonsingular Implementation of the Mellor-Yamada Level 2.5 Scheme in the NCEP Meso model. National Centers for Environmental Prediction Office Note, #437, 61, 2002.

Seite 15: [52] Gelöscht **Julia Curio** **01.08.16 23:13**

and

Seite 15: [52] Gelöscht **Julia Curio** **01.08.16 23:13**

and

Seite 15: [53] Formatiert **Julia Curio** **01.08.16 23:13**

Schriftart:Kursiv

Seite 15: [53] Formatiert **Julia Curio** **01.08.16 23:13**

Schriftart:Kursiv

Seite 15: [54] Formatiert **Julia Curio** **01.08.16 23:13**

Einzug: Links: 0 cm, Hängend: 0,85 cm

Seite 15: [55] Gelöscht **Julia Curio** **01.08.16 23:13**

and

Seite 15: [55] Gelöscht **Julia Curio** **01.08.16 23:13**

and

Seite 15: [56] Formatiert **Julia Curio** **01.08.16 23:13**

Schriftart:Kursiv

Seite 15: [56] Formatiert **Julia Curio** **01.08.16 23:13**

Schriftart:Kursiv

Seite 15: [57] Formatiert **Julia Curio** **01.08.16 23:13**

Einzug: Links: 0 cm, Hängend: 0,75 cm

Seite 15: [58] Gelöscht **Julia Curio** **01.08.16 23:13**

and

Seite 15: [58] Gelöscht **Julia Curio** **01.08.16 23:13**

and

Seite 15: [59] Formatiert **Julia Curio** **01.08.16 23:13**

Schriftart:Kursiv

Seite 15: [59] Formatiert **Julia Curio** **01.08.16 23:13**

Schriftart:Kursiv

Seite 15: [60] Gelöscht **Julia Curio** **01.08.16 23:13**

and

Seite 15: [60] Gelöscht **Julia Curio** **01.08.16 23:13**

and

Seite 15: [61] Formatiert **Julia Curio** **01.08.16 23:13**

Schriftart:Kursiv

Seite 15: [62] Formatiert **Julia Curio** **01.08.16 23:13**

Schriftart:Kursiv

Seite 15: [62] Formatiert **Julia Curio** **01.08.16 23:13**

Schriftart:Kursiv

Seite 15: [63] Gelöscht **Julia Curio** **01.08.16 23:13**

Ma, Y., Wang, Y., Wu, R., Hu, Z., Yang, K., Li, M., Ma, W., Zhong, L., Sun, F., Chen, X., Zhu, Z., Wang, S., and Ishikawa, H.: Recent advances on the study of atmosphere-land interaction observations on the Tibetan Plateau. Hydrology and Earth System Sciences, 13(7), 1103–1111. doi:10.5194/hess-13-1103-2009, 2009.

Seite 15: [63] Gelöscht **Julia Curio** **01.08.16 23:13**

Ma, Y., Wang, Y., Wu, R., Hu, Z., Yang, K., Li, M., Ma, W., Zhong, L., Sun, F., Chen, X., Zhu, Z., Wang, S., and Ishikawa, H.: Recent advances on the study of atmosphere-land interaction observations on the Tibetan Plateau. Hydrology and Earth System Sciences, 13(7), 1103–1111. doi:10.5194/hess-13-1103-2009, 2009.

Seite 15: [63] Gelöscht **Julia Curio** **01.08.16 23:13**

Ma, Y., Wang, Y., Wu, R., Hu, Z., Yang, K., Li, M., Ma, W., Zhong, L., Sun, F., Chen, X., Zhu, Z., Wang, S., and Ishikawa, H.: Recent advances on the study of atmosphere-land interaction observations on the Tibetan Plateau. Hydrology and Earth System Sciences, 13(7), 1103–1111. doi:10.5194/hess-13-1103-2009, 2009.

Seite 15: [64] Formatiert **Julia Curio** **01.08.16 23:13**

Schriftart:Kursiv

Seite 15: [64] Formatiert **Julia Curio** **01.08.16 23:13**

Schriftart:Kursiv

Seite 16: [65] Gelöscht **Julia Curio** **01.08.16 23:13**

Medeiros, B., Hall, A., & Stevens, B.: What controls the mean depth of the PBL? Journal of Climate, 18(16), 3157–3172. doi:10.1175/JCLI3417.1, 2005.

Seite 16: [65] Gelöscht **Julia Curio** **01.08.16 23:13**

Medeiros, B., Hall, A., & Stevens, B.: What controls the mean depth of the PBL? Journal of Climate, 18(16), 3157–3172. doi:10.1175/JCLI3417.1, 2005.

Seite 16: [65] Gelöscht **Julia Curio** **01.08.16 23:13**

Medeiros, B., Hall, A., & Stevens, B.: What controls the mean depth of the PBL? Journal of Climate, 18(16), 3157–3172. doi:10.1175/JCLI3417.1, 2005.

Seite 16: [66] Gelöscht **Julia Curio** **01.08.16 23:13**

, 1439–1455

Seite 16: [66] Gelöscht **Julia Curio** **01.08.16 23:13**

, 1439–1455

Seite 16: [67] Gelöscht **Julia Curio** **01.08.16 23:13**

and

Seite 16: [67] Gelöscht **Julia Curio** **01.08.16 23:13**

and

Seite 16: [68] Gelöscht Julia Curio 01.08.16 23:13

., Reudenbach, C., Thies, B., and Bendix, J.:

Seite 16: [68] Gelöscht Julia Curio 01.08.16 23:13

., Reudenbach, C., Thies, B., and Bendix, J.:

Seite 16: [69] Formatiert Julia Curio 01.08.16 23:13

Schriftart:Kursiv

Seite 16: [69] Formatiert Julia Curio 01.08.16 23:13

Schriftart:Kursiv

Seite 16: [70] Gelöscht Julia Curio 01.08.16 23:13

and

Seite 16: [70] Gelöscht Julia Curio 01.08.16 23:13

and

Seite 16: [70] Gelöscht Julia Curio 01.08.16 23:13

and

Seite 16: [70] Gelöscht Julia Curio 01.08.16 23:13

and

Seite 16: [70] Gelöscht Julia Curio 01.08.16 23:13

and

Seite 16: [71] Gelöscht Julia Curio 01.08.16 23:13

and

Seite 16: [71] Gelöscht Julia Curio 01.08.16 23:13

and

Seite 16: [72] Formatiert Julia Curio 01.08.16 23:13

Schriftart:Kursiv

Seite 16: [72] Formatiert Julia Curio 01.08.16 23:13

Schriftart:Kursiv

Seite 16: [73] Gelöscht Julia Curio 01.08.16 23:13

and

Seite 16: [73] Gelöscht Julia Curio 01.08.16 23:13

and

Seite 16: [74] Formatiert Julia Curio 01.08.16 23:13

Schriftart:Kursiv

Seite 16: [74] Formatiert Julia Curio 01.08.16 23:13

Schriftart:Kursiv

Seite 16: [75] Gelöscht Julia Curio 01.08.16 23:13

and

Seite 16: [75] Gelöscht Julia Curio 01.08.16 23:13

and

Seite 16: [76] Gelöscht Julia Curio 01.08.16 23:13

and

Seite 16: [76] Gelöscht Julia Curio 01.08.16 23:13

and

Seite 16: [77] Formatiert Julia Curio 01.08.16 23:13

Schriftart:Kursiv

Seite 16: [77] Formatiert Julia Curio 01.08.16 23:13

Schriftart:Kursiv

Seite 16: [78] Gelöscht Julia Curio 01.08.16 23:13

Vachon, R., and

Seite 16: [78] Gelöscht Julia Curio 01.08.16 23:13

Vachon, R., and

Seite 16: [79] Formatiert Julia Curio 01.08.16 23:13

Schriftart:Kursiv

Seite 16: [79] Formatiert Julia Curio 01.08.16 23:13

Schriftart:Kursiv

Seite 16: [80] Gelöscht Julia Curio 01.08.16 23:13

,

Seite 16: [80] Gelöscht Julia Curio 01.08.16 23:13

,

Seite 16: [81] Formatiert Julia Curio 01.08.16 23:13

Schriftart:Kursiv

Seite 16: [81] Formatiert Julia Curio 01.08.16 23:13

Schriftart:Kursiv

Seite 16: [82] Gelöscht Julia Curio 01.08.16 23:13

N., Shukla, J., Tomas, R. A., Yanai, M., and Yasunari, T.:

Seite 16: [82] Gelöscht Julia Curio 01.08.16 23:13

N., Shukla, J., Tomas, R. A., Yanai, M., and Yasunari, T.:

Seite 16: [83] Gelöscht Julia Curio 01.08.16 23:13

,

Seite 16: [83] Gelöscht Julia Curio 01.08.16 23:13

,

Seite 16: [84] Gelöscht Julia Curio 01.08.16 23:13

Wilks, D. S.: Statistical Methods in the Atmospheric Sciences: An Introduction. Academic Press, 1995.

Seite 16: [84] Gelöscht Julia Curio 01.08.16 23:13

Wilks, D. S.: Statistical Methods in the Atmospheric Sciences: An Introduction. Academic Press, 1995.

Seite 16: [84] Gelöscht **Julia Curio** **01.08.16 23:13**

Wilks, D. S.: Statistical Methods in the Atmospheric Sciences: An Introduction. Academic Press, 1995.

Seite 16: [84] Gelöscht **Julia Curio** **01.08.16 23:13**

Wilks, D. S.: Statistical Methods in the Atmospheric Sciences: An Introduction. Academic Press, 1995.

Seite 16: [84] Gelöscht **Julia Curio** **01.08.16 23:13**

Wilks, D. S.: Statistical Methods in the Atmospheric Sciences: An Introduction. Academic Press, 1995.

Seite 16: [85] Gelöscht **Julia Curio** **01.08.16 23:13**

Yang, K., Koike, T., Fujii, H., Tamura, T., Xu, X., Bian, L., and Zhou, M.: The Daytime Evolution of the Atmospheric Boundary Layer and Convection over the Tibetan Plateau: Observations and Simulations. Journal of the Meteorological Society of Japan, *82*(6), 1777–1792. doi:10.2151/jmsj.82.1777, 2004.

Seite 16: [85] Gelöscht **Julia Curio** **01.08.16 23:13**

Yang, K., Koike, T., Fujii, H., Tamura, T., Xu, X., Bian, L., and Zhou, M.: The Daytime Evolution of the Atmospheric Boundary Layer and Convection over the Tibetan Plateau: Observations and Simulations. Journal of the Meteorological Society of Japan, *82*(6), 1777–1792. doi:10.2151/jmsj.82.1777, 2004.

Seite 17: [86] Gelöscht **Julia Curio** **01.08.16 23:13**

Seite 20: [87] Gelöscht **Julia Curio** **01.08.16 23:13**

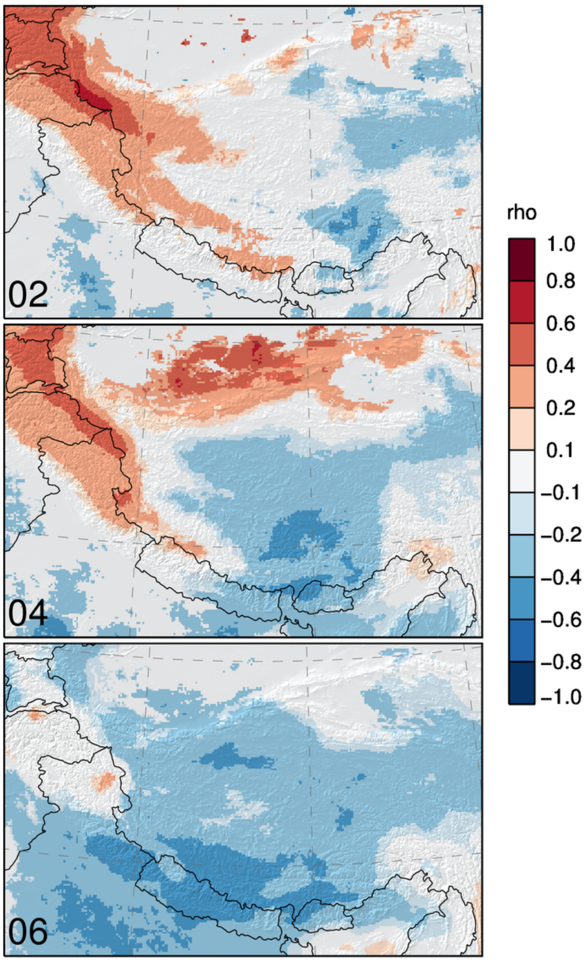


Fig.

Seite 20: [88] Gelöscht **Julia Curio** **01.08.16 23:13**

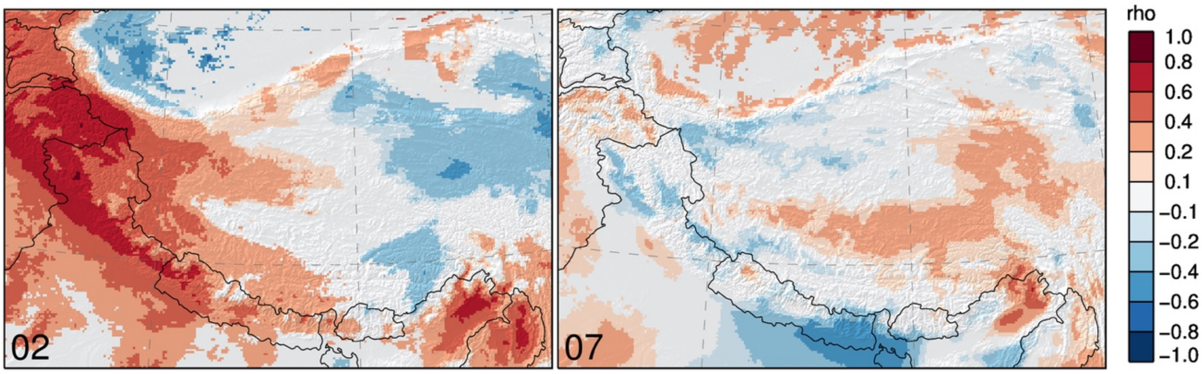


Fig.

Seite 21: [89] Gelöscht **Julia Curio** **01.08.16 23:13**

February (02) and July (07). Positive correlations are denoted in red, while negative correlations are denoted in blue.

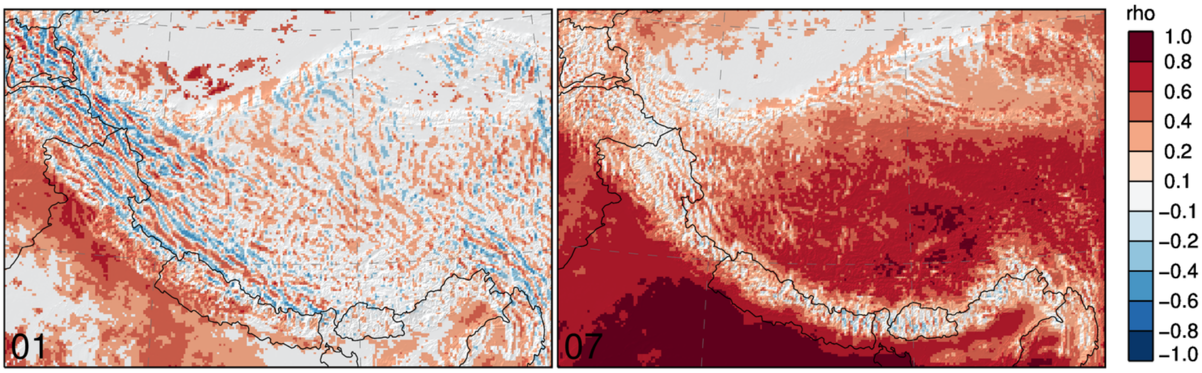
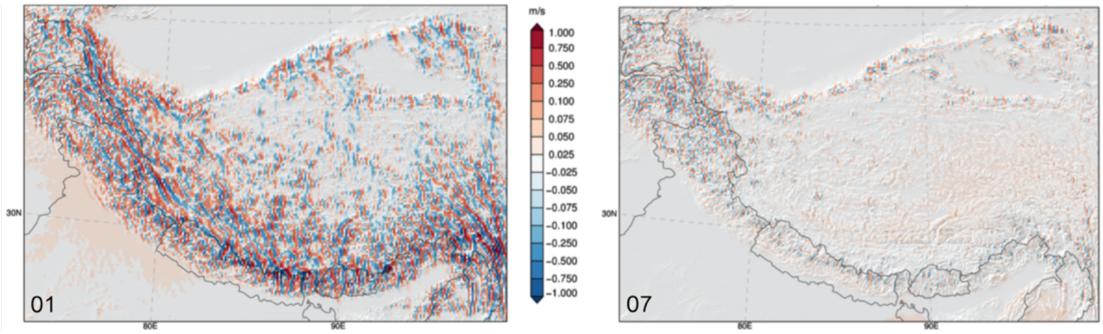


Fig. 5: Coefficient of correlation (rho) between vertical wind speed at 300 hPa (W300) and precipitation for January (01) and July (07).

Seite 22: [90] Gelöscht **Julia Curio** **01.08.16 23:13**



Seite 22: [91] Auf Seite 23 verschoben (Verschiebung Nr. 6) Julia Curio 01.08.16 23:13

Fig. 6: Mean vertical wind speed at 300 hPa for January (01) and July (07).

Seite 22: [92] Gelöscht **Julia Curio** **01.08.16 23:13**

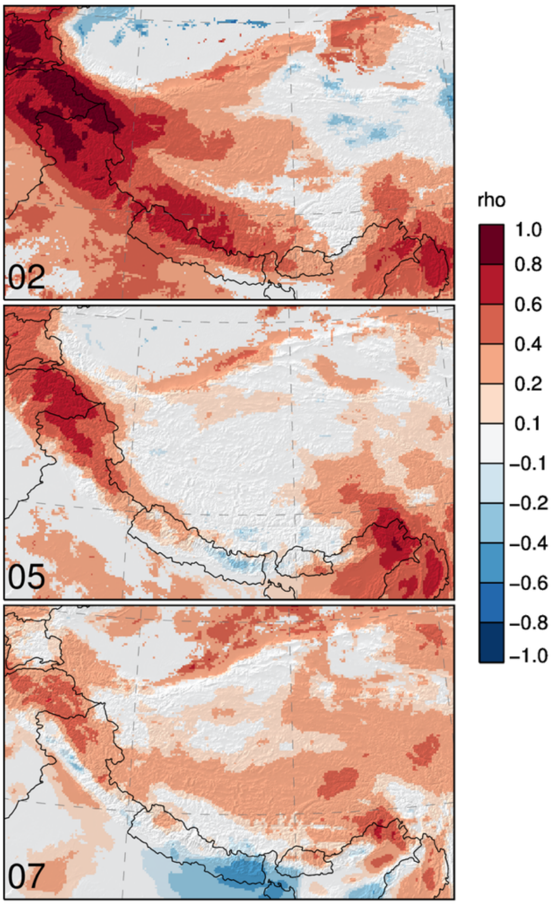


Fig. 7:

Seite 24: [93] Gelöscht **Julia Curio** **01.08.16 23:13**

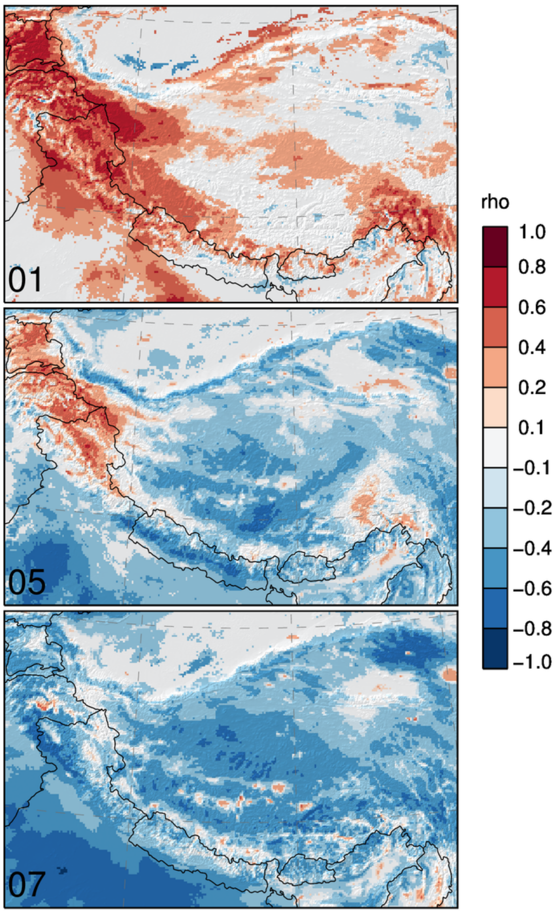


Fig. 8:

Seite 25: [94] Gelöscht **Julia Curio** **01.08.16 23:13**

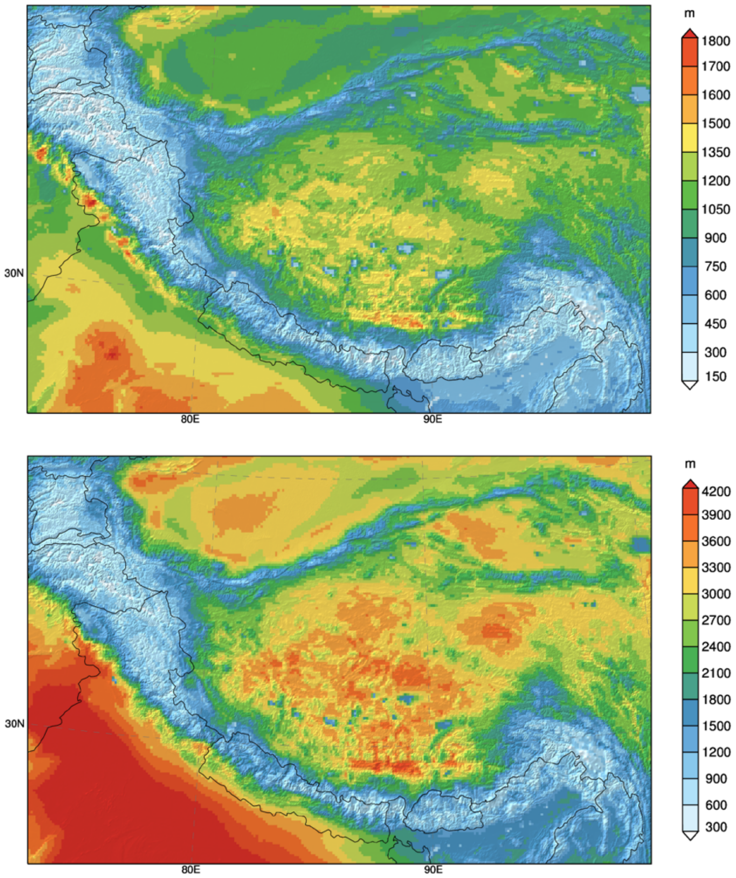
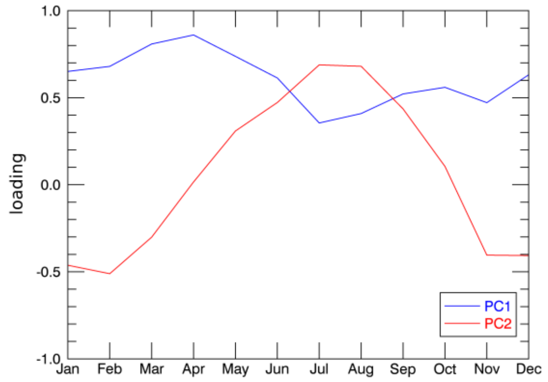
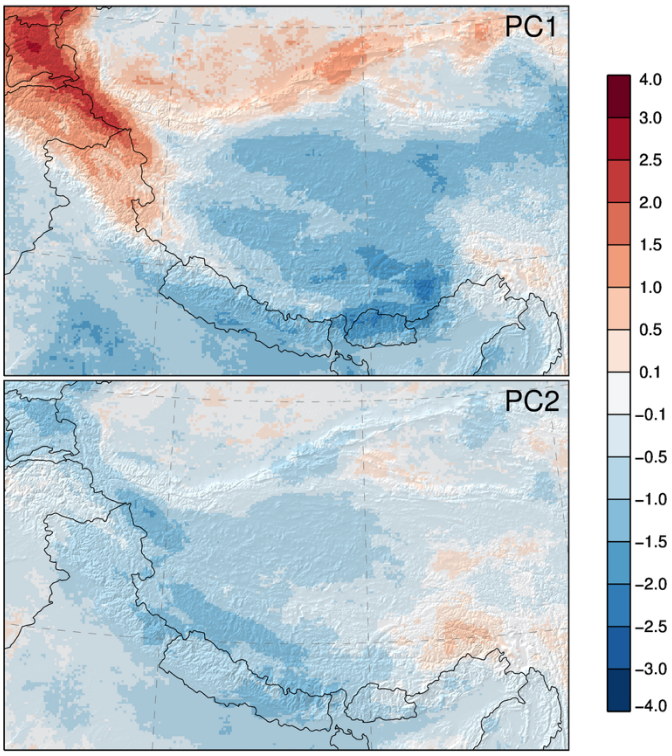


Fig. 9: Planetary boundary layer height (m) daily mean (top) and mean daily maximum (bottom) in May (2001-2013).



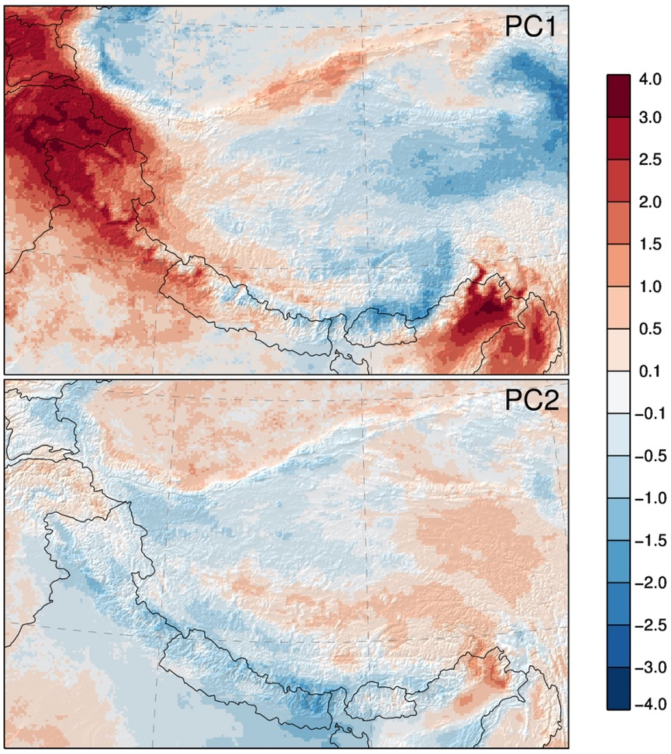
(a)

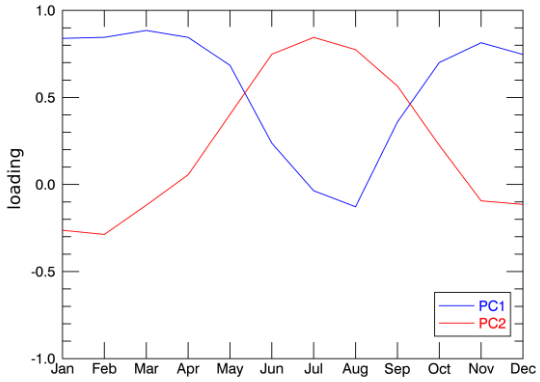


(b)

Seite 26: [95] Gelöscht **Julia Curio** **01.08.16 23:13**

(a)

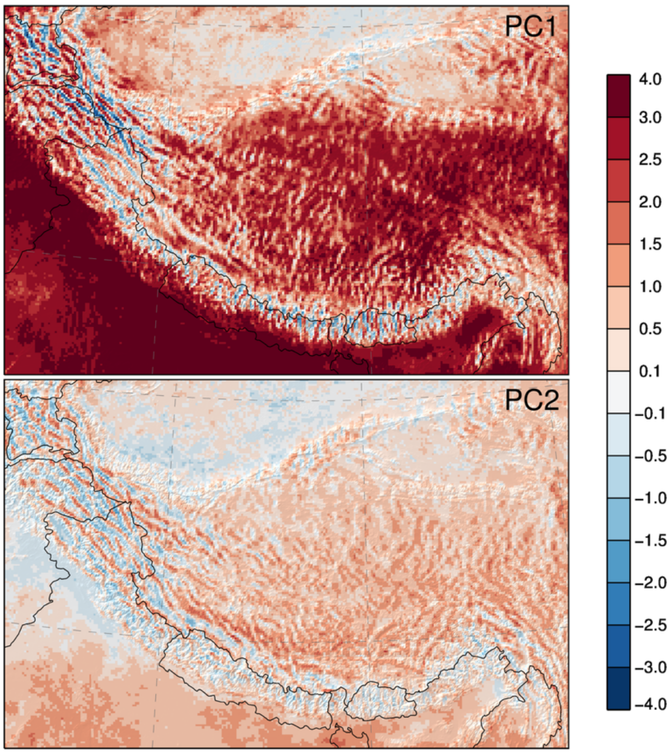


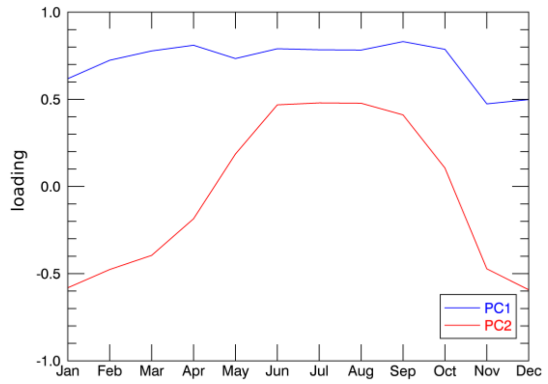


(b)

Seite 27: [96] Gelöscht **Julia Curio** **01.08.16 23:13**

(a)

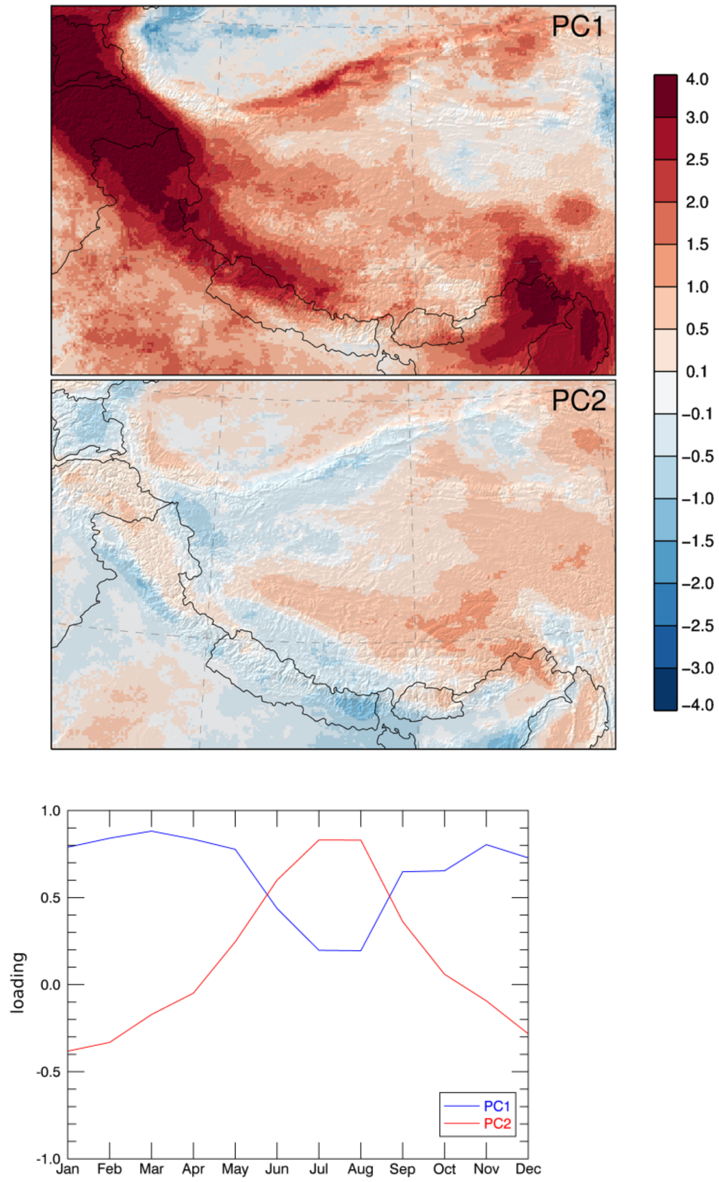

PC1
PC2
4.0
3.0
2.5
2.0
1.5
1.0
0.5
0.1
−0.1
−0.5
−1.0
−1.5
−2.0
−2.5
−3.0
−4.0



(b)

Seite 28: [97] Gelöscht **Julia Curio** **01.08.16 23:13**

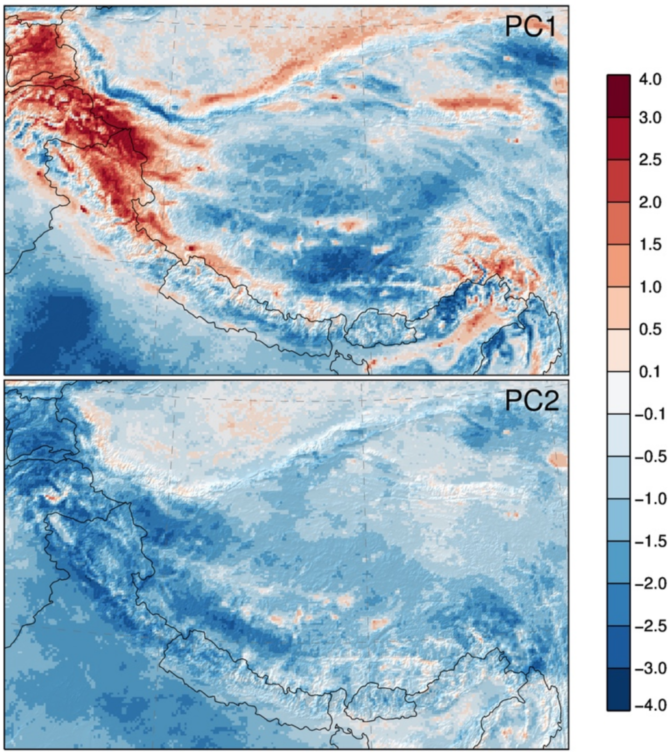
(a)

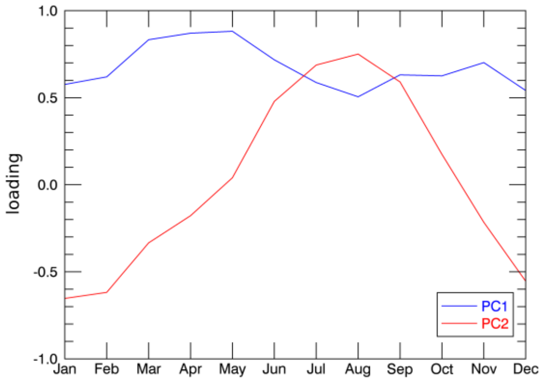


(b)

Seite 29: [98] Gelöscht **Julia Curio** **01.08.16 23:13**

(a)





(b)

Figure 14. Scores of first two principal components PC1 and PC2 for the correlation between planetary boundary layer height (PBLH) and precipitation **(a)** (positive values are denoted in red, while negative values are denoted in blue) and the monthly loadings **(b)** for both PCs.

List of relevant changes made in the manuscript

- We replaced the correlation plots for selected months with the plots for all months provided in the supplementary material of an earlier version of this manuscript.
- We excluded the height of the planetary boundary layer from the list of selected dynamic variables, as suggested by anonymous referee 1.
- We also removed the vertical wind speed at the model level 10 from the manuscript, because the results are very similar to the results for the 300 hPa vertical wind speed.
- We added the plots of the additional analyses conducted for the author response to the manuscript or the supplementary material.
- We added more references regarding the selection of the dynamic precipitation control.

Seasonality and spatial variability of dynamic precipitation controls on the Tibetan Plateau

Julia Curio[1,2] and Dieter Scherer[1]

[1]Chair of Climatology, Technische Universität Berlin, Berlin, Germany
[2]National Centre for Atmospheric Science, Department of Meteorology, University of Reading, Reading, UK

Correspondence to: J. Curio (j.curio@reading.ac.uk)

Abstract. The Tibetan Plateau (TP) is the origin of many large Asian rivers, which provide water resources for large regions in South and East Asia. Therefore, the water cycle on the TP and adjacent high mountain ranges, in particular the precipitation distribution and variability play an important role for the water availability for billions of people in the downstream regions of the TP.

The High Asia Refined analysis (HAR) is used to analyse the dynamical factors that influence the precipitation variability in the TP region, including the factors resulting in the enhancement and suppression of precipitation. Four dynamical fields that can influence precipitation are considered, the 300 hPa wind speed and wind speed two kilometres above ground, the 300 hPa vertical wind speed, and the atmospheric water transport. The study focusses on the seasonality and the spatial variability of the precipitation controls and their dominant patterns. Results show that different factors have different effects on precipitation in different regions and seasons. This depends mainly on the dominant type of precipitation, convective or frontal/cyclonic precipitation. Additionally, the study reveals that the mid-latitude westerlies have a high impact on the precipitation distribution on the TP and its surroundings year-round and not only in winter.

1 Introduction

The Tibetan Plateau has been called the “world water tower” (Xu et al., 2008), and is the origin of many rivers in high Asia, which provide water for billions of people downstream in South and East Asia. The TP is located in the transition zone between the mid-latitude westerlies (Schiemann et al., 2009) and the Indian and East Asian summer monsoon systems (Webster et al., 1998). The TP shapes the hydro-climate of downstream regions by its influence on the large-scale circulation (Hahn and Manabe, 1975), caused by its large extent and height.

Since precipitation is a key feature of the water cycle of High Asia, it is important to analyse the factors controlling precipitation variability. Identifying which dynamic factors influence the precipitation may also help to estimate the impact of future climate change on precipitation variability.

Previous studies have stated that precipitation over the TP is controlled by the westerlies in winter and the Indian and East Asian summer monsoon in summer (e.g. Hren et al., 2009; Tian et al., 2007; Yang et al., 2014). This assumption is derived only from the precipitation timing, but Curio et al. (2015) and Mölg et al. (2014) already shown that the mid-latitude westerlies also have an impact on the summer precipitation.

There are many studies that have explored the influence of atmospheric circulation modes, e.g. the North Atlantic Oscillation, the Arctic Oscillation, and El Nino/Southern Oscillation, on the climate and precipitation in high Asia and on the monsoon systems (e.g. Bothe et al., 2009; Liu et al., 2015; Liu and Yin, 2001; Rüthrich et al., 2015). Less attention has been paid to the underlying processes controlling the precipitation variability over the TP and the surrounding high mountain ranges.

Gelöscht: [2]Department
Gelöscht: julia
Gelöscht: tu-berlin.de
Gelöscht: moisture
Gelöscht: and especially
Gelöscht: plays
Gelöscht: regions
Gelöscht: Based on the
Gelöscht: we
Gelöscht: of dynamic factors on
Gelöscht: , enhancing or suppressing
Gelöscht: development. We selected six
Gelöscht: controls, the horizontal and vertical wind speed at
Gelöscht: in about
Gelöscht: , and the planetary boundary layer height. Focus of the
Gelöscht: are
Gelöscht: se
Gelöscht: The results
Gelöscht: precipitation controls
Formatiert: Abstand Vor: 6 Pt.
Gelöscht: , often
Gelöscht: in the
Gelöscht: regions
Gelöscht: the impact of
Gelöscht: and
Gelöscht: . This may
Formatiert: Schriftfarbe: Text 1
Gelöscht: development and amounts, since if a specific control in a specific region and time is identified, one would be aware that a strengthen or weakening of this precipitation control has distinct impact on precipitation development
Formatiert: Schriftfarbe: Text 1
Gelöscht: on
Gelöscht: based
Gelöscht: on
Gelöscht: 3
Gelöscht: ed
Gelöscht: also
Gelöscht: There are many studies on the influence of atmospheric circulation modes, e.g. the North Atlantic Oscillation, the Arctic Oscillation, and El Nino/Southern Oscillation, on climate and precipitation in high Asia and on the monsoon systems (e.g. Bothe et al., 2009; Liu et al., 2015; Liu and Yin, 2001; Rüthrich et al., 2015). Less attention is drawn to the underlying processes controlling precipitation development on the TP and the surrounding high mountain ranges.
... [1]

The High Asia Refined analysis (HAR) (Maussion et al., 2014), which is the result of the dynamical downscaling of an operational analysis and which covers more than thirteen years at high spatial and temporal resolution, provides the opportunity for a process based analysis of the precipitation and its variability.

The starting point of this study is the seasonality of the precipitation over the TP and the evaluation of the factors that control the precipitation over the TP and the surrounding high mountain ranges. This focusses on the timing, location and strength of the factors that influence precipitation and its variability.

The main aim of this study is to describe the spatial and temporal correlation of selected dynamical variables and precipitation to reveal the underlying mechanisms through which the variables influence precipitation and therefore act as controls of precipitation variability.

We selected four variables as dynamic precipitation controls: horizontal wind speed at 300 hPa and in about two kilometres above ground, the vertical wind speed at 300 hPa, and the vertically integrated atmospheric water transport. It is known that these factors have an influence on precipitation variability, but on the basis of coarse resolution datasets it was not possible to analyse the relations spatially and temporally differentiated like it is now with the High Asia Refined analysis (HAR).

The different precipitation controls have effects on different spatial scales. While the horizontal and vertical wind speed at 300 hPa (WS300 and W300) are large-scale controls, the horizontal wind speed in the boundary layer (WS10) is active on the meso-scale. The atmospheric water transport (AWT) connects the large- with the meso-scale because it is effective on both scales and across large distances. We do not claim completeness for the list of precipitation controls, but assume that these four factors belong to the most important dynamic precipitation controls. It is important to keep in mind, that the precipitation controls are not independent from each other and can have combined effects on precipitation variability or neglect each other, this will not be in the focus of the current study.

In the following we will shortly introduce the selected precipitation controls and their possible impacts on precipitation variability.

The horizontal wind speed at the 300 hPa level has two main effects on precipitation variability. High WS300 can inhibit or cut off deep convection and thus supress precipitation development (e.g. Findell et al., 2003; and Zhang and Atkinson,1995). In this case only shallow convection can form which does not lead to considerable precipitation amounts. Mölg et al. (2009) showed that convective precipitation events on tropical mountain summits correspond to low horizontal wind speeds. On the other hand, higher wind speeds can have positive effects on moisture advection and orographic lifting, and can, in lower levels, enhance evaporation from the surface and therefore convection (e.g. Johansson and Chen, 2003; Roe, 2005). This process is most interesting during the warm half of the year, when surface moisture from local sources like lakes, soil moisture, the active layer of permafrost, snow and glacier melt is available. Moisture recycling plays an important role for precipitation on the TP (e.g. Araguás-Araguás et al., 1998; Trenberth, 1999), on average more than 60% of moisture needed for precipitation falling on the inner TP are provided by the TP itself (Curio et al., 2015).

The core of the Subtropical Westerly Jet (SWJ) occurs at the 200 hPa level. Over the Tibetan Plateau the jet reaches down to 300 hPa and still has an effect there and also in lower levels. This was shown for the HAR by Maussion et al. (2014). The strength and location of the jet influences the hydro-climate of the Tibetan Plateau and central Asia (e.g. Schiemann et al., 2009). Especially the precipitation seasonality in the north-western parts of the study region is related to the position of the jet (Schiemann et al., 2008).

Garreaud (2007) pointed out that stronger than normal low level westerlies lead to more precipitation on the windward side of meridionally orientated mountain ranges (orographic precipitation), while high wind speeds at mountain tops leads to rather dry conditions because of intensified downdrafts. This process is called rain shadow effect. But he also shows this

Formatiert: Abstand Vor: 0 Pt., Abstand zwischen Absätzen gleicher Formatierung einfügen, Keine Absatzkontrolle, Leerraum zwischen asiatischem und westlichem Text nicht anpassen, Leerraum zwischen asiatischem Text und Zahlen nicht anpassen

Gelöscht: a gridded global data set

Gelöscht: , on a daily basis, gives us

Gelöscht: to analyse the data

Gelöscht: .

Formatiert: Schriftart:Times, Deutsch

Gelöscht: Starting

Gelöscht: precipitation

Gelöscht: on

Gelöscht: question which

Gelöscht: on

Gelöscht: Therefore, we want to examine which ... [2]

Gelöscht: on

Gelöscht: development and how strong it is. Aim

Formatiert: Schriftfarbe: Text 1

Gelöscht: between controls

Formatiert: Schriftfarbe: Text 1

Formatiert: Schriftfarbe: Text 1

Gelöscht: spatially and temporally differentiated.

Gelöscht: six

Gelöscht: ,

Gelöscht: and vertical

Gelöscht: and the height of the planetary boundary layer.

Gelöscht: development

[1] verschoben

Gelöscht: six

Gelöscht: development

[2] nach unten: The selection of precipitation control ... [3]

Gelöscht: Back and Bretherton, 2005; Garreaud, 2007 ... [4]

[1] nach oben: The different precipitation controls ha ... [5]

Gelöscht: While the horizontal and vertical wind spee ... [6]

Gelöscht: development

Gelöscht: development

Gelöscht: .

[3] verschoben

Gelöscht: with low horizontal wind speeds. On the ot ... [7]

Formatiert: Schriftfarbe: Blau

Gelöscht: ... [8]

[3] nach oben: , on average more than 60% of moistu ... [9]

Gelöscht: Back and Bretherton (2005) found that th ... [10]

Formatiert ... [11]

[4] nach unten: The negative effect of high horizon ... [12]

Gelöscht: While the positive effect occurs in regions ... [13]

Gelöscht: luv

could lead to more precipitation on the lee side because more cloud particles are advected and disturbances can overcome the topographic barrier with the help of higher wind speeds, which would lead to more frontal or cyclonic precipitation. This case already shows that it depends on many factors which influence each of the dynamic controls has on precipitation and that the of influence highly varies regarding time and space.

The influence of the vertical wind speed on precipitation depends on the direction of the vertical wind, whether it is an updraft or a downdraft (Rose et al., 2003). Updrafts have a positive impact on precipitation because they can boost or enhance convection and are a key element for orographic precipitation on the windward side of mountain ranges, while downdrafts (e.g. on the lee side of mountain ranges) and subsidence lead to inhibition of convection and cloud dispersal. The expectation is that we have mainly positive correlations of vertical wind with precipitation, high upward winds cause higher precipitation and higher downward winds cause less precipitation.

Atmospheric water transport (AWT) is not only a dynamic precipitation control because it is a product of atmospheric moisture content and wind speed (and direction). The positive effect of AWT on precipitation variability due to moisture supply is described in, for example, Barros et al., 2006; and Giovannetone et al., 2009. Therefore, we assume that there is always a positive correlation between AWT and precipitation. But high AWT does not automatically lead to precipitation development, what was for example shown by Curio et al. (2015) for the Qaidam Basin where the prevailing atmospheric subsidence inhibits convection.

The main objectives of the study are two-fold:

i. to analyse the impact of selected dynamic variables on the spatial and temporal variability of precipitation,

ii. to examine whether the different factors that control precipitation variability act in the same way in different regions and at different times,

iii. to gain a better understanding of the role of the mid-latitude westerlies and the summer monsoon systems on the precipitation distribution on the TP.

In the following section, we describe the data and methods used in this study. Section 3 present the precipitation seasonality on the TP and adjacent mountain ranges based on the HAR using a cluster analysis. Focus of the study is the period 2001-2013. Afterwards we analyse the correlations between the four selected dynamic variables and precipitation, regarding seasonality and spatial variability. A principal component analysis of this correlations is then used to detect the dominant patterns. The results and their uncertainties are discussed in section 4. In section 5, we draw conclusions from our study.

2 Data and methodology

2.1 The High Asia Refined analysis

This study is based on the High Asia Refined analysis (HAR). The HAR has been produced using the advanced research version of the Weather and Research Forecasting model (WRF-ARW, Skamarock and Klemp, 2008) version 3.3.1 to dynamically downscale the Operational Model Global Tropospheric Analyses (final analyses, FNL; data set ds083.2), a global gridded data set. The HAR dataset, its modelling, forcing, and re-initialization strategies are described in detail by Maussion et al., (2011, 2014). The HAR data set currently covers the period from October 2000 to September 2014 and will be updated continuously. The first domain of the HAR encompasses most parts of south-central Asia with a spatial resolution of 30 km and temporal resolution of 3 h (HAR30). High Asia and the Tibetan Plateau are the focus of a second nested domain with a spatial resolution of 10km and temporal resolution of 1 h

Gelöscht: development

Gelöscht: .

Gelöscht: luv

Gelöscht: We

Gelöscht: , because AWT delivers moisture for precipitation from remote sources to the TP (regions where precipitation occurs).

Gelöscht: The height of the planetary boundary layer (PBLH) shows the turbulent mixing of the lower atmosphere. It is influenced by solar forcing, turbulent processes, convective activity (Yang et al., 2004), moisture content and temperature of surface and air, and wind speed. Gentine et al. (2013) point out that dry soil surface accelerates the growth of the PBL. The TP has one of the highest PBLs in the world, due to its high altitude and strong solar forcing, but the TP PBL is not fully understood yet because there are only few observations. During daytime in spring and summer the PBL is higher than in the other seasons in this region (Patil et al., 2013) and can exceed heights of 3000 m or more (Ma et al., 2009; Yang et al., 2004) in some regions on the TP due to strong solar forcing and convective activity. The horizontal wind speed influences the PBLH by facilitating the m ... [14]

Formatiert: Schriftfarbe: Text 1

Gelöscht: the

Formatiert: Schriftfarbe: Text 1

Gelöscht: controls on precipitation development spa ... [16]

Formatiert ... [15]

Formatiert ... [17]

Formatiert: Schriftfarbe: Text 1

Gelöscht: if precipitation controls have always and ... [18]

Gelöscht: there are opposing effects active in

Formatiert: Schriftfarbe: Text 1

Gelöscht: sub-regions,

Formatiert: Schriftfarbe: Text 1

Formatiert: Schriftart:Times, Schriftfarbe: Text 1

Gelöscht: and

Gelöscht: for

Gelöscht: Here we first

Formatiert: Abstand Vor: 6 Pt.

Gelöscht: six

Gelöscht: precipitation controls

Gelöscht: Methods

Formatiert: Abstand Vor: 6 Pt.

Gelöscht: HAR data set

Formatiert: Abstand Vor: 6 Pt.

Gelöscht: is generated

Gelöscht: Skamarock and Klemp, 2008

Gelöscht: for

Gelöscht: downscaling of

Gelöscht: , and the validation of the results

Gelöscht:

Gelöscht: .

(HAR10). A map of the HAR10 domain and its location in the parent domain HAR30 are shown in Fig. 1. In this study we analyse the processes on the TP and the surrounding high mountain ranges and therefore use the HAR10 data only. The calculation of the vertically integrated atmospheric water transport can be found in Curio et al. (2015). For this study the HAR data are used on a daily basis.

The HAR data set was validated by Maussion et al. (2014) by comparison with rain-gauge observations from the National Climatic Data Center (NCDC) and the satellite derived gridded precipitation data from the Tropical Rainfall Measuring Mission (TRMM). The HAR shows a slightly positive bias in comparison with station data, 0.17 mm/day for HAR10 (0.26 mm/day for TRMM 3B43 product). The comparison with TRMM shows that HAR captures the general features of precipitation seasonality, variability, and spatial distribution. Maussion et al. (2014) found that the HAR10 precipitation averaged over the domain shows 15% more precipitation than TRMM, but these differences are assumed to be related to the well- known underestimation of snowfall and light rain by TRMM. Convective precipitation is simulated in agreement with results from literature, but one has to keep in mind that the model uses a parameterization scheme for cumulus convection. A spatial resolution of 10 km is not high enough to resolve cumulus convection. The HAR is able to reproduce orographic precipitation features as documented by Bookhagen and Burbank (2010). Maussion et al. (2014) state that these qualitative considerations cannot provide a quantitative uncertainty value. Curio et al. (2015) compared the HAR30 atmospheric water transport (AWT) with ERA-Interim. They found similar patterns; the differences being related to the different spatial resolutions and thus a better representation of the underlying topography by the HAR. In the HAR data, the blocking of AWT from the Bay of Bengal by the Himalayas is more pronounced, and the results show the importance of meridionally orientated high mountain valleys for moisture supply to the Tibetan Plateau. We have compared the 300 hPa wind of the HAR10 data set with ERA-Interim. Figure R1 shows that they are in a good agreement with each other. Due to the daily reinitialization strategy used to generate the HAR data set, the wind fields in higher levels cannot evolve far away from the forcing data as this is possible for longer model runs. The question how large the uncertainties of the HAR data and especially precipitation are and how we can estimate them, is a topic which should be investigated more in detail. Since there are no other gridded data sets with a comparable high temporal and spatial resolution, the possibilities to validate the HAR are generally limited and will be subject of future research.

2.2. Methodology

The selection of precipitation controls relies on well studied relations of these factors with precipitation (e.g. Back and Bretherton, 2005; Garreaud, 2007; Shinker et al., 2006) but these controls were not investigated at high spatial and temporal resolution in high mountain Asia until now.

The current study is based on the HAR10 data set for the study period 2001-2013 (all entire years available). Starting point of this study is an analysis of the precipitation seasonality on the TP using the k-means clustering method (e.g. Wilks, 1995). The percentages of monthly contribution to annual precipitation and not the precipitation amounts were used to define seven classes with different precipitation seasonality. This has the advantage that, in an area like high Asia where the differences in precipitation amounts vary strongly between regions and seasons, the regions were made comparable by this method. We conducted the cluster analysis with other numbers of classes (5-9), but the chosen number of seven classes led to the best ratio between coherent patterns and sufficient distinction between classes. This analysis follows the approach of Maussion et al. (2014) who used the clustering to detect glacier accumulation regimes on the TP. Their input data were restricted to glaciated areas only. Our current analysis expands the data base to the entire TP and surrounding regions, using all grid points of the HAR10 domain. For all further analysis daily averaged HAR data are used. Because we are only interested in

Gelöscht:

Gelöscht: ... [19]

[2] verschoben

precipitation days, the data set is stratified using a daily precipitation threshold. This is done month-wise. For example, all analyses for July depend on the data basis of each July day during the period 2001-2013; these are 31*13 days, 403 days in total. Precipitation days for a grid point are defined as days with a mean daily precipitation rate of at least 0.1 mm, which is a commonly used minimum value to define precipitation days (e.g. Polade et al., 2014; Liu et al., 2011; Bartholy et al., 2010; Frei et al., 1998). The threshold was basically used to filter out numerical artefacts and not to exclude events from the data base.

The daily precipitation rate at each grid point is calculated as the mean precipitation rate for all grid points within an area of 15*15 grid points around the specific grid point, respectively. The time mask for precipitation days is then applied to the four variables used as precipitation controls. The number of precipitation days can vary distinctly between regions and seasons. Each of the dynamical variables is correlated with the precipitation using the Spearman rank correlation. This is done month-wise for all precipitation days in a specific month during the study period and for each grid point in the HAR10 data set. Using correlations avoids problems associated with the exact precipitation rates/amounts falling on the TP, which are hard to measure and to model exactly. The Spearman rank correlation uses the ranks of the values and not the values itself, which makes the correlations independent of the real data and more robust against outliers. This makes it easier to compare regions with very different precipitation amounts with each other and helps to reduce the effects of extreme events on the correlation results. We are aware of the fact that ranking the data leads to a slight information loss compared to the real values. We are sure that for our purpose the advantages are bigger than the disadvantages. Only correlations, which are significant at the 95% level, are plotted. The statistical significance of the correlations was tested using a two tailed test to determine the deviation from zero (Numerical Recipes, The Art of Scientific Computing, 1992). The calculation oft the statistical significance is described more in detail in the supplementary material. A principal component analysis (PCA) is performed for the results of the correlations with precipitation to detect the dominant relationships.

3 Results

3.1 Precipitation seasonality

Figure 2 shows the seven defined classes of precipitation regime, and the mean annual cycle of monthly precipitation percentage in each class. It is clearly visible that the TP and the surrounding high mountain ranges show a spatial variability regarding precipitation seasonality. A class with a precipitation maximum in summer and a minimum in winter is dominant on the central TP and south of the Himalayas in India, Nepal and Pakistan (blue, class 6). This class is the monsoonal precipitation class, because the precipitation percentage increases from June on, the onset period of the Indian summer monsoon. During July and August more than 50% of the annual precipitation is falling in this regions, while from October to May the monthly precipitation amount is below 5 % of the annual precipitation. The yellow class has a much broader and less pronounced summer precipitation maximum and the increasing and decreasing proceed with similar rates. The annual cycle of precipitation in this class is determined by the seasonal cycle of solar forcing and therefore convective activity. The green class represents a transition zone between the monsoonal and convective classes where the monsoon can have an influence but is not dominant. This means that both monsoonal precipitation and/or only solar forced convective precipitation can occur.

The naming convention does not mean that the monsoonal class precipitation is not of convective nature, but it should emphasize that the precipitation (development/variability) is influenced by the monsoon, which is associated with the advection of tropical air masses. The

Formatiert: Abstand Vor: 0 Pt., Nach: 12 Pt., Abstand zwischen Absätzen gleicher Formatierung einfügen, Keine Absatzkontrolle, Leerraum zwischen asiatischem und westlichem Text nicht anpassen, Leerraum zwischen asiatischem Text und Zahlen nicht anpassen

Gelöscht: .

Gelöscht: therefore

Gelöscht: on

Gelöscht: precipitation controls

Gelöscht: then

Gelöscht: ,

Gelöscht: t

Gelöscht: ,

Gelöscht: Only significant

Gelöscht: , with a level of significance of 0.05, are plotted. Following this, a principal component analysis (PCA) was performed for the correlations between controls and precipitation to detect the dominant patterns. ... [20]

Gelöscht: regarding

Gelöscht: starting point of this study is the precipitation seasonality on the TP which was analysed by Maussion et al. (2014) using the k-means clustering method (e.g. Wilks, 1995) and will be deepened in the current study. The percentages of monthly contribution to annual precipitation

Gelöscht: precipitation amounts were used to define seven classes with

Gelöscht: seasonality. This has the advantage that in an area like high Asia where the differences in precipitation amounts vary strongly between regions and seasons, the regions were made comparable by this method. We conducted the cluster analysis

Gelöscht: numbers of classes, but

Gelöscht: chosen number

Gelöscht: seven classes led to the best ratio between coherent patterns and sufficient distinction between classes

Formatiert: Schriftfarbe: Text 1

Formatiert: Keinen Abstand zwischen Absätzen gleicher Formatierung einfügen

Formatiert: Abstand Vor: 6 Pt.

Gelöscht: are

Gelöscht: intensive

Formatiert: Schriftfarbe: Text 1

Formatiert: Schriftfarbe: Text 1

Gelöscht: laying

Formatiert: Schriftfarbe: Text 1

Gelöscht: so called

Formatiert: Schriftfarbe: Text 1

Gelöscht: represents a region of mixing between monsoonal and convective classes, there we can have

Formatiert: Schriftfarbe: Text 1

Gelöscht: (green). This class represents a transition ... [21]

Formatiert ... [22]

monsoonal class is a subset of the convective class. The timing and strength of the precipitation maximum provides an indication for different forcing. In the monsoonal class the precipitation maximum is higher, starts during the Indian Summer Monsoon onset and persists for a shorter time period.

The monsoonal class is divided into a northern and southern part by the Himalayas. The grey-blue class experiences its precipitation maximum in winter and is dominated by the influence of the mid-latitude westerlies. This class occurs mainly in the Pamir/Karakoram/western Himalayas (PKwH) region, as one coherent pattern, and additionally in the eastern part of the Tarim Basin. The precipitation maximum is much lower, but the minimum values are higher than in the classes dominated by summer precipitation, which shows that the intra-annual variability is lower, the values vary between 15% and 5%, but are never below 5% in the mean. This could lead to the assumption that the influence of the mid-latitude westerlies is more constant year-round, while the monsoon has a stronger but temporally more limited influence on precipitation on the TP.

The light blue class exhibits a more evenly distributed seasonality of precipitation, during spring and summer with a minimum in November. This class surrounds the grey-blue cluster, at the southern flank of the western Himalayas (western notch), in the south-eastern TP, and in the eastern Tarim Basin. It is interesting that the region in the south east of the TP, where the Brahmaputra Channel enters the TP, belongs to a different class than the surroundings, which are divided between the three convectively dominated classes, blue, yellow and green. Maybe there is stronger influence by AWT, which would make this region more similar to the surrounding of PKwH region regarding the factors controlling precipitation variability. Another possible reason could be the occurrence of extra-tropical cyclones which propagate eastward along the Himalayas and are then terrain-locked by the eastern notch of the Himalayas (Norris et al., 2015). This would lead to higher moisture supply to the region and therefore higher amounts of orographic precipitation. This kind of terrain locking of the westerly flow in winter is described in detail for the western notch of the Himalayas by Norris et al. (2015). This mechanism would explain the higher shares of winter precipitation in the region around the Brahmaputra channel and the affiliation to the same class occurring at the southern flank of western Himalayas in the western notch.

The remaining two classes, red and purple, almost only appear in the Tarim Basin. They are both characterized by a spring and early summer precipitation regime, but also show some differences. The amount of precipitation in the purple class increases sharply from March to May/June were the maximum with a value of slightly above 20% occurs. The decrease is even sharper so that in July already only 6 % of the annual precipitation occur. The annual cycle of the red class seems to be delayed relative to the purple one and the period of maximum precipitation is only one-month long. In spring the values are lower but higher in late summer and autumn, while they are almost the same during winter.

The high mountain ranges of the Himalayas and Kunlun and Qilian Shan exhibit a complex structure of different classes over relatively short distances and therefore exhibit no coherent patterns. This holds true also for the border area between the Karakoram and the Tarim Basin. The mountainous region of the Pamir and Karakoram are represented by only one class, which implies that this region is mainly influenced by one atmospheric forcing (mid-latitude westerlies) or that different controls have the same impact in this region. The other mountain ranges lie in regions where an interplay of different controls occur, and the temporal and spatial variability is larger on smaller scales.

3.2 Correlation of dynamic variables and precipitation

3.2.1 Horizontal wind speed

a) Horizontal wind speed at 300 hPa (WS300)

Gelöscht: That there is a forcing difference between the two classes is clearly visible in the

Formatiert: Schriftfarbe: Text 1

Gelöscht: which is higher and later in

Formatiert: Schriftfarbe: Text 1

Gelöscht: and

Formatiert: Schriftfarbe: Text 1

Gelöscht: period

Formatiert: Schriftfarbe: Text 1

Gelöscht: only

Formatiert: Schriftfarbe: Text 1

Formatiert: Schriftart:Arial, 16 pt, Schriftfarbe: Text 1, Deutsch

Gelöscht: The monsoonal class is divided in a northern and southern part by the Himalayas.

Formatiert: Schriftart:Times, Schriftfarbe: Text 1, Deutsch

Formatiert: Abstand Vor: 0 Pt., Abstand zwischen Absätzen gleicher Formatierung einfügen

Gelöscht: seasonality, with

Gelöscht: precipitation and

Gelöscht: occurs as a frame for

Gelöscht: development.

Gelöscht: ,

Gelöscht: a bit

Gelöscht: against

Formatiert: Abstand Vor: 0 Pt., Abstand zwischen Absätzen gleicher Formatierung einfügen

Gelöscht: on

Gelöscht: may

Gelöscht: s

Gelöscht:

Formatiert: Zeilenabstand: 1.5 Zeilen

Gelöscht: controls

Formatiert: Schriftart:Arial

Gelöscht: We only show the months with the most prominent features. Figures with the correlation of each dynamic control with precipitation for all months are provided in the supplemental material for completenes... [23]

The correlations between WS300 and precipitation are shown in Figure 3. There are high positive correlations in winter in the PMwH region; this is the time of the year when the majority of precipitation falls in this region (e.g. Curio et al., 2015; Maussion et al., 2014). The precipitation in the PMwH region is mainly cyclonic/frontal precipitation and is associated with western disturbances (Dimri et al., 2015). There are only negative correlations in the southern and eastern parts of the TP in winter, which enlarges over spring and covers mainly the whole central and north-eastern TP and large parts of the central Himalayas with the highest negative correlations in the central TP. The reason for the negative correlations in these regions is that they are dominated by convective precipitation (e.g. Maussion et al., 2014) and higher wind speeds in winter inhibit the deep convection. This also explains why there are almost everywhere negative correlations in summer. The region of negative summer correlations covers almost the same area as the convective and monsoonal precipitation classes (Fig. 2) combined, so the impact of WS300 explains some of the precipitation classes. In spring there is a second region with positive correlations north of the TP in the Tarim Basin and the bordering Kunlun and Qilian Shan. This area is reached by the northern branch of the mid-latitude westerlies which delivers moisture for precipitation. The area around the Brahmaputra Channel exhibits slightly positive correlations, due to enhanced moisture transport by higher wind speeds. The region of high positive winter correlations exhibits no or slightly positive correlations in only a small area in summer and in some parts of the region the positive correlations are replaced by negative ones. Since there is a non negligible amount of precipitation falling in this region in summer (~ 20-40%, see cluster 0 and 5 in Fig. 2), the lag/absence of positive correlations and the occurrence of negative correlations means that a different factor controls precipitation variability and/or the same control works in a different way due to higher shares of convective precipitation, especially in the eastern parts of the Pamir Karakoram region.

b) Horizontal wind speed at model level 10 (WS10)

Figure 4 shows, that the correlations between WS10 and precipitation are positive in the PMwH region in winter as they are for WS300, but the region is larger, especially the region with correlations > 0.6. The reason for the positive correlations is again the enhanced moisture supply due to higher wind speeds and therefore also more orographic precipitation. The positive correlations in the Brahmaputra Channel region (and south of it) are more pronounced and the structure of the Brahmaputra Channel itself is clearly visible. The moisture supply is enhanced due to strengthened winds from the south, bringing moisture from the Indian Ocean to the Himalayas. There are high positive correlations between the WS10 and precipitation over the Tibetan Plateau in summer, while the correlations with WS300 are negative in summer. This is because of the fact that the wind speed in the boundary layer can enhance evapotranspiration from the surface (e.g. lakes; snow, glacier and permafrost melt), which leads to more moisture in the lower atmosphere available for precipitation. This correlation again emphasizes the importance of moisture recycling on the TP. In winter the correlations on the TP are mainly negative because the effect of enhanced evapotranspiration is not active due to the fact that all potential moisture sources are frozen during this time of the year. Strong negative correlations occur south of the Himalayas and in northern parts of India in summer. When the air flow from the south hits the mountain barrier parts of the flow are redirected southeast and northwest. The flow becomes divergent which forces the air above to decent, which in turn leads to unfavourable conditions for growing convection and therefore precipitation.

3.2.2 Vertical wind speed

The correlations between vertical wind speed at 300 hPa (Fig. 5) and precipitation are mainly positive due to the positive effect of ascending air motion on precipitation development, as

Gelöscht: provided

Gelöscht: for selected months.

Formatiert: Abstand Vor: 6 Pt.

Gelöscht: .

Gelöscht: T

Gelöscht: Curio et al., 2015; Maussion et al., 2014). The precipitation in this region is mainly cyclonic/frontal precipitation, which benefits from enhanced moisture supply due to higher wind speeds. On the TP we have only negative correlations in the southern and eastern parts in winter, while this area

Gelöscht: Reason

Gelöscht: this is

Gelöscht: dominance of

Gelöscht: in this region

Gelöscht:). Higher

Gelöscht: and therefore have a negative effect on precipitation development

Gelöscht: has

Gelöscht: shape like

Gelöscht: put together

Gelöscht: u

Gelöscht: t

Gelöscht: r

Gelöscht: which lays

Gelöscht: to

Gelöscht: in

Gelöscht: , because

Gelöscht: almost no

Gelöscht: (

Gelöscht: -

Gelöscht: % of annual

Gelöscht:) during summer months in

Gelöscht: /

Gelöscht: (Maussion et al., 2014).

Gelöscht: (February) like

Gelöscht: Reason

Gelöscht: here

Formatiert: Abstand Vor: 6 Pt., Keine Absatzkontrolle, Leerraum zwischen asiatischem und westlichem Text nicht anpassen, Leerraum zwischen asiatischem Text und Zahlen nicht anpassen

Gelöscht: in

Gelöscht:) and model level 10 (not shown because of high similarity; see supplemental material

Gelöscht: like assumed

expected, especially in summer when most of the precipitation is convective. Therefore, the positive correlations are higher in summer than in winter when almost no precipitation falls on the TP, although the mean vertical wind speeds (up- and downdrafts) are higher in winter than in summer (Fig. 6). This shows that higher values of one precipitation control alone do not necessarily lead to higher correlations and therefore more precipitation, but that usually other conditions favourable for precipitation development have to occur. This supports the interpretation that precipitation variability is mostly caused by combined effects of different precipitation controls.

The high mountain ranges of the Pamir and Karakoram show a pattern of alternating positive and negative correlations between vertical wind speed and precipitation. It was expected that the correlations between the vertical wind speed would be positive at both sides of the mountain ranges. But the negative correlations can be explained physically. If an air flow hits a mountain range, the barrier causes orographic induced flow patterns, with updrafts on the windward side and downdraft on the lee side of the mountain range. This causes the precipitation to be smaller on average on the lee side because the downdrafts supress precipitation development. In the case of a stronger horizontal flow to the mountains, there is stronger moisture advection and orographic precipitation and therefore the downdrafts on the lee side are no longer able to supress precipitation. This leads to the simultaneous occurrence of precipitation and downdrafts which is the reason for the negative correlation patterns on the lee side of mountain ranges found in the western parts of the study region.

3.2.3 Atmospheric water transport (AWT)

Figure 7 shows the correlations between AWT and precipitation. The entire study region is dominated by positive correlations during the year (Fig. 7). The highest positive correlations occur in winter and early spring in the PKwH region, where the correlation coefficient exceeds 0.8 in most regions. This is the time of the year when the maximum precipitation occurs in this region (Fig. 2). The annual contribution of convective precipitation in this region is below 10% (Maussion et al., 2014), but the region exhibits orographic precipitation triggered by the advection of moist air masses with the westerly flow and westerly disturbances (Cannon et al., 2014). Therefore, higher moisture supply leads naturally to more precipitation. The positive correlations in the western parts of the study region persist during the course of the year, even if their extent and strength varies. The positive correlations extend to the TP, the whole Himalayan arc, and along the northern border of the TP (Kunlun and Qilian Shan). These seem to be the moisture supply routes along the branches of the mid-latitude westerlies.

A second centre of positive correlation which is persistent is found in the extreme southeast of TP, the region where the Brahmaputra Channel enters the TP. This region exhibits less convective precipitation on annual time scales (Maussion et al., 2014), but it is surrounded by regions with high convective precipitation rates. This explains the fact that this region belongs to a different precipitation seasonality class than its surroundings (Fig. 2). In January and February, the Himalayan arc exhibits mostly positive correlations and connects the area in the western parts of the domain with the other positive centre in the south-eastern TP around the Brahmaputra channel.

The spatial minimum of the positive correlations occurs in May, whereas the correlations are very high ($r > 0.6$) in the western and south-eastern centres. In May the central TP exhibits no significant correlations which may be caused by the fact that the AWT is very low on the TP in May (Curio et al., 2015). From then on the area with positive correlations enlarges but the strength of correlation decreases.

The minimum values of the positive correlations occur in July and August. But then there are positive correlations in the central TP, but they are not as high as in the western and south-eastern parts of the domain during winter and spring. This shows that the precipitation during

Gelöscht: points out/emphasizes

Formatiert: Schriftfarbe: Automatisch

Formatiert: Schriftfarbe: Automatisch

Gelöscht: assumption

Formatiert: Schriftfarbe: Automatisch

Gelöscht: development

Formatiert: Schriftfarbe: Blau

Formatiert: Schriftfarbe: Text 1

Formatiert: Abstand Vor: 0 Pt.

Gelöscht: negative correlations in the high

Formatiert: Schriftfarbe: Text 1

Gelöscht: Karakorum in winter could be an aggregation problem, due to

Formatiert: Schriftfarbe: Text 1

Gelöscht: use of daily means. This

Gelöscht: the case if we, for example, have a day with strong downdrafts in the mean, but during a shorter time

Formatiert: Schriftfarbe: Text 1

Gelöscht: day we have updrafts leading to precipitation, which are not seen in the mean for the day. Other possible reasons for

Formatiert: Schriftfarbe: Text 1

Formatiert: Schriftfarbe: Text 1

Gelöscht: could be large systems of frontal/cyclonic precipitation, which can still rain

Formatiert ... [24]

Gelöscht: , where as a consequence of the flow over the mountain ranges already

Formatiert: Schriftfarbe: Text 1

Gelöscht: occur.

Formatiert: Schriftfarbe: Text 1

Gelöscht: would lead

Formatiert ... [25]

Gelöscht: and precipitation, and therefore

Formatiert: Schriftfarbe: Text 1

Gelöscht: correlations

Formatiert: Schriftfarbe: Text 1

Gelöscht: provides…hows the correlations between AWT and precipitation. The entire study region is dominated by positive correlations during the year (Fig. 7), like we assumed before. There are only few regions and months where negative correlations occur, in the Tarim Basin during winter, at the central Himalayas (and the southern slopes) during summer.…. The highest positive correlations occur in winter and early spring in the PKwH region, where the correlation coefficient r …xceeds 0.8 in large areas…ost regions. This is the time of the year where… the maximum precipitation maximum …ccurs in this region (Fig. 2). The annual p…ontribution of convective precipitation in this regi ... [26]

Gelöscht: ,… t…his region exhibits also …ess conv ... [27]

Gelöscht: now

Gelöscht: now we have …hen there are positive ... [28]

this time of the year is mostly convective and that the moisture is coming from local sources, so that the advection of moist air masses is less important. In large areas of the domain the precipitation maximum occurs in July and August, ~30% of the annual precipitation fall on the central and southern TP during this time (Maussion et al., 2014).
The regions where the highest positive correlations occur are the regions where the precipitation maximum occurs during winter, matching the grey-blue precipitation seasonality class (Fig. 2). There are only a few regions and months where negative correlations occur, in the Tarim Basin during winter, and in the central Himalayas and northern India during summer.

3.3. Principal components

So far the spatio-temporal variability of correlation between dynamical variables and precipitation for the TP and surrounding high mountain ranges have been discussed. To detect the dominant patterns in the relationship between the different variables and precipitation and to find the time of the year a control is most efficient, we conducted a principal component analysis (PCA) for each of the correlation sets. Because the dominant modes are the main interest only the first two principal components (PCs) are analysed, which typically explain most of the variance of the data and also can explain important processes. For completeness, plots for all PCs can be found in the supplemental material of this study. The explained variance of PC1 lies between 40% and 50% and at around 20% for PC2 for all sets of correlations. The higher PCs explain lower shares of variance, less than 10% already for PC3 and only 1% for PC12.
Figure 8 shows the scores of the first two principal components for the correlation between WS300 and precipitation and their monthly loadings. PC1 shows a pattern which looks like the winter pattern of the correlations in the western parts of the study region, the spring pattern of the northern region, and the summer pattern of the TP were combined. This is confirmed by the annual cycle of loadings for PC1. The highest positive loadings occur in winter and spring, which means that these months have the largest share of the dominant pattern. The loadings are high all year-round but highest in spring and lowest in July. This implies that this pattern is not particularly influenced by the monsoon system or if so just in the onset period. We assume that the still relatively high loading is a result of the fact that there are high solar forcing and therefore convective activity on the TP which is negatively influences by higher wind speeds at 300 hPa. The loadings of the second PC (PC2) show a completely different annual cycle. They are strongly negative in winter and strongly positive in summer, it is just in the transition seasons that the loadings are around zero. For this pattern winter and summer play a similar role, even with opposing arithmetic signs. This is an annual cycle pattern. The first two PCs together account for ~ 60% of the total variance of the data.
The first PC (PC1) for the correlation between WS10 and precipitation (Fig. 9a) shows a pattern dominated by the winter and early spring situation, high positive scores in the PKwH region and the region around the Brahmaputra Channel and negative scores on the central and eastern TP. The loadings (Fig. 9b) are very high (~ 0.8) from November to April. Only in July and August the loadings are slightly negative. The positive correlations during summer on the TP are not visible in PC1, they occur in PC2 which has loadings that have a direct opposing annual cycle, meaning high positive values in Summer and slightly negative in winter. The first two PCs together explain ~ 65% of the variance in the data.
All months exhibit high loadings for PC1 of the correlation between the vertical wind speed and precipitation. Fig. 10 shows the scores and the loadings of the first two PCs for the correlation of W300 with precipitation. Summer and early autumn conditions have the largest impact, while loadings are lowest in winter, but still positive. Therefore, the high positive correlations in summer on the TP and in the lowlands south of the Himalayas are the dominant pattern, meaning that the vertical wind speed as a precipitation control is most effective during

Gelöscht: whereby
Gelöscht: are falling
Gelöscht: . ... [29]
Gelöscht: We described
Formatiert: Abstand Vor: 6 Pt.
Gelöscht: controls
Gelöscht: .
Gelöscht: leading or
Gelöscht: this relations
Gelöscht: out in which
Gelöscht: we are interested in
Gelöscht: we
Gelöscht: analyse
Gelöscht:),
Gelöscht: set. The patterns in the higher PCs, which
Gelöscht: , will be subject of a further study.
Gelöscht: Explained
Gelöscht: 10 provides the maps of
Gelöscht: we have layered
Gelöscht: .
Gelöscht: corroborated
Gelöscht: on
Gelöscht: very much
Gelöscht: rather
Gelöscht: we have
Gelöscht: has a negative correlation to high
Gelöscht: highly
Gelöscht: highly
Gelöscht: of
Gelöscht: 11a
Gelöscht: which is
Gelöscht: 11b
Gelöscht: (both levels)
Gelöscht: 12
Gelöscht: , the PCs for the correlation between W10 and precipitation are not shown because of high similarity to W300.
Gelöscht: strongest

that time of the year, but has a mostly positive impact on precipitation year-round. PC2 exhibits much lower values. The annual cycle of the loadings shows, that winter and summer both have high loadings (~ 0.5), but with different signs, positive in summer and negative in winter. Spring and autumn exhibit very low factor loadings and are more or less only transition periods between winter and summer. The first two PCs together explain ~ 70% of the variance in the data.

The loadings of the first two PCs of the correlation between AWT and precipitation (Fig. 11b) exhibit a similar annual cycle as the loadings of the correlation between WS300 and precipitation. For PC1 the loadings are high (between 0.6 and 0.9) in winter, spring and autumn and low in summer (~ 0.2). This again emphasizes the finding that AWT is a precipitation control mainly in regions and seasons where moisture advection and frontal/cyclonic precipitation is dominant. The pattern of PC2 (Fig. 13a) is important mainly by summer months (loadings > 0.8 in July and August), while the winter months exhibit negative loadings.

In summary, the annual cycle of the loadings for each of the first two PCs, show a similar annual cycle. PC1 is mostly dominated by all seasons except summer, and mainly by the winter and spring situations. Whereas PC2 is determined by summer conditions. Winter conditions also have high loadings but with negative sign, while spring and autumn only represent transition periods between these situations.

4 Discussion

4.1. General discussion of results

A main result of the current study is the high negative correlations between the 300 hPa horizontal wind speed and precipitation on the TP. This confirms the findings of Mölg et al. (2014), who showed that the flow strength at the 300 hPa level above the TP, during the onset period of the Indian Summer Monsoon, exhibits strong negative correlations with precipitation, and explains 73% of the inter-annual mass balance variability of the Zhadang glacier, located at the Nyainqenthangla range in the central TP. They argue that weak flow conditions favour convective cell growth. This together with the high positive correlations, in regions and seasons where frontal/cyclonic precipitation is dominant, shows the strong influence of the Subtropical Westerly Jet (mid-latitude westerlies) not only on the western parts of the study region but also on the TP itself, which previously has mostly been described as mainly influenced by the monsoon system (Hren et al., 2009; Tian et al., 2007; Yang et al., 2014).

Previous studies have stated that the precipitation on the TP is controlled by the mid-latitude westerlies in winter and the Indian and East Asian summer monsoon in summer (e.g. Hren et al., 2009; Tian et al., 2007; Yang et al., 2014). This assumption is based only on precipitation timing, but Curio et al. (2015) and Mölg et al. (2014) have already shown that the mid-latitude westerlies also have an impact on summer precipitation. The current study highlights their findings by the detection of the negative influence of the high horizontal wind speeds on precipitation (development, variability, amount) on the TP in summer.

Spiess et al. (2015) showed that in summer, increased horizontal wind speeds at 400 hPa have a positive effect on the height of the equilibrium line altitude at glaciers in different regions on the TP, they assumed that this could be caused by a reduction of convective precipitation due to high wind speeds. Exactly this process is shown by the strong negative correlations between horizontal wind speed at 300 hPa and precipitation in summer on the TP (Fig. 3).

The identified positive correlations of the wind speed in the boundary layer with precipitation in summer on the TP agree with the findings of Back & Bretherton (2005) who detected positive correlations between near surface wind speed and precipitation only when convection can be triggered easily. Their study region was the Pacific ITCZ, but we assume that their findings are

Gelöscht: both

Gelöscht: algebraic

Gelöscht:

Gelöscht: 3

Gelöscht: like

Gelöscht: composed

Gelöscht: Regarding the correlation between PBLH and precipitation the dominant pattern PC1 (Fig. 14), which explains ~47% of the variance in the data, is dominated by the spring, which is clearly visible by comparing the pattern of PC 1 with the correlations in May (Fig. 8). All other months exhibit high positive loadings (>0.5), too, but August has the lowest share. The dominant pattern represents the spring pattern, which shows the transition between the winter (positive correlations) and the summer conditions (negative correlations). PC2 is mainly influenced by the high negative correlations dominant summer. The winter months exhibit high negative loadings. The different behaviour above the large lakes on the central TP is visible in both PCs.

Formatiert: Abstand Vor: 0 Pt.

Gelöscht: also

Gelöscht: arithmetic

Gelöscht:

Formatiert: Abstand Vor: 18 Pt.

Formatiert: Schriftart:Arial, Deutsch

Gelöscht:

Formatiert: Abstand Vor: 12 Pt.

Gelöscht: One

Formatiert: Abstand Vor: 6 Pt.

Gelöscht: are

Gelöscht: in 300hPa

Gelöscht: Mölg et al. (2013)

Gelöscht: during this period in the regions influenced by monsoon

Gelöscht: They only explain the correlations the other way round and

Gelöscht: favours

Gelöscht: detected in the current study

Gelöscht: was so far

Gelöscht: s

Gelöscht: 2013)

Gelöscht: d

Gelöscht: have

[5] verschoben

Formatiert: Schriftfarbe: Automatisch

Gelöscht: shown

also valid for the TP in summer, where the convective activity is high and enough moisture is available at the surface.

The fact that the positive correlation of AWT with precipitation in summer on the central TP are not as high as in the western parts of the study region in winter, means that here the convection is able to produce precipitation using the moisture from local sources, which emphasizes the importance of moisture recycling, as shown by Curio et al. (2015) using HAR data and by Chen et al. (2012), Joswiak et al. (2013) and Kurita and Yamada (2008), among others. Nevertheless, AWT still has a positive effect on precipitation, but it is not an essential control during this time of the year on the central TP.

Additionally, we calculated the vertically integrated atmospheric moisture content for the HAR and repeated the calculation of correlation for this variable. The results (Fig. S5; see supplementary material) show high positive correlations between the atmospheric moisture content and precipitation throughout the year, as expected. The correlation patterns can only explain parts of the precipitation variability on the TP. This highlights how highly effective the dynamic controls are on precipitation variability, differentiated in space and time.

4.2 Sources of uncertainties

As always the uncertainty of the results mainly depends on the accuracy of the data itself, the aggregation of hourly data to daily means, and the statistical methods used to analyse the data. The HAR precipitation and other variables, e.g. wind speed and direction, and temperature, have been validated against other gridded data sets, global reanalyses and remote sensing data, and observations from weather stations by Maussion et al. (2011, 2014), as described in section 2.1.

NCDC station data were used to compare the results of the precipitation clustering approach with observations. Figure 12 shows the precipitation classes for the station data, and for the associated HAR grid points, and whether the obtained cluster regarding the mean annual cycle of monthly precipitation contribution to annual precipitation match (green dots) or not (red dots). 27 of the 65 stations (41.5%) fall in the same cluster as the nearest HAR grid point. For 38 stations (58.5%) this is not true, but most of them fall in cluster with very similar annual cycle or in cluster which are spatially very close to the cluster to which the HAR grid point belongs. This is especially the case in the mountain regions in the western, the south-eastern, and north-eastern parts of the domain where at least four different cluster occur on very small spatial scales. Table 1 shows which percentage of the stations, which all should be in one specific class regarding their associated HAR grid points, falls in which of the seven possible classes. One has to take into account that there is always a distance up to a few kilometres between the NCDC stations and the respectively associated HAR grid point. This also can cause huge differences between the elevation/altitude of stations and grid points due to the complex topography of the study region, which in turn has an effect on the precipitation distribution. Additionally, the quality of the station data is not always satisfying and the time series often show gaps, leading to a smaller data base.

The HAR10 and ERA-Interim wind speed at 300 hPa of has been compared. They are in a good agreement with each other (Fig. S6; see supplementary material). Due to the daily reinitialization strategy used to generate the HAR data set, the wind fields in higher levels cannot evolve far away from the forcing data as this is possible for longer model runs.

We decided to use the wind speed at the 300 hPa level because the wind shear in this height more strongly suppresses deep convection than at the 200 hPa level where the core of the jet lays. Also we assumed that the results would not change overall using the wind speed in 200 hPa. To proof that, we repeated the correlation analysis between wind speed and precipitation for the wind speed at 200 hPa (Fig. S7; see supplementary material). The results are very similar. The correlations at the 300 hPa level (Fig. 3) are slightly higher because the negative effect of higher wind speeds on precipitation by cutting off deep convection is higher at this

Gelöscht: t

Gelöscht: already with

Gelöscht: great

Gelöscht: like

Gelöscht: has

Gelöscht: Spiess et al. (2015) showed that in summer

[5] nach oben: increased horizontal wind speeds at 400 hPa have a positive effect on the height of the equilibrium line altitude at glaciers in different regions on the TP, they assumed that this could be caused by a reduction of convective precipitation due to high wind speeds. Exactly this process is shown by the strong negative correlations between horizontal wind speed at 300 hPa and precipitation in summer on the TP (Fig. 3).

Formatiert: Schriftfarbe: Automatisch

Gelöscht: ... [30]

Formatiert: Abstand Vor: 18 Pt.

Formatiert: Abstand Vor: 6 Pt., Keinen Abstand zwischen Absätzen gleicher Formatierung einfügen

Gelöscht: the

Gelöscht: were

Gelöscht:).

Gelöscht: Due to the use of

level than in 200 hPa.

We varied the k for clustering from 5 to 9 (Fig. S8; see supplementary material). We found 7 to be the optimal k for the recent study since it gave us good coherence within the classes and sufficient distinctions between them, like you say and we state in the manuscript. We determined this qualitatively by looking at the plots for the different numbers of clusters. We first conducted the cluster analysis with 5 (Fig. S8 (a)) clusters like Maussion et al. (2014). But since we included a much higher number of grid points (we analysed the entire Tibetan Plateau), the results for the areas included in both analyses look slightly different especially in the Karakoram and Tien Shan. By increasing the number of cluster to 6 (Fig. S8 (b)), one cluster that covers most parts of the northern part of the study region, northern Tibetan Plateau and Tarim Basin, breaks up in two cluster. Setting the number to 7 (Fig. S8 (c)), we get more variation in the Karakoram and Tien Shan which looks more similar to the cluster distribution achieved by Maussion et al. (2014). Using a higher number of clusters (Fig. S8 (d) and (e)) led to the occurrence of more clusters of smaller size which are not as distinct from each other as the larger ones. In general, it would be interesting to have more cluster to get a higher spatial differentiation. But by increasing the cluster number the spatial coherence decreases and therefore the interpretability also decreases. We decided to use seven clusters as a compromise between higher spatial differentiation and less spatial coherence. Since the core areas of the clusters stay stable while changing the number of clusters we assume that the clustering approach is suitable to analyse the seasonality of precipitation on the TP.

Of course using different parameterizations and higher spatial resolutions would change the precipitation values and the spatial and temporal distribution of the precipitation. But we assume that this would not change the the main results of this study since we use rank correlations which are independent of the mean values and scaling of the input variables.

Using correlations we avoid problems regarding the exact precipitation rates falling on the TP. Additionally the use of the monthly percentage of annual precipitation as input for the cluster analyses, to detect the precipitation seasonality in different regions of the TP, makes it possible to compare regions, which exhibit distinct different precipitation amounts. This is a general aspect to keep in mind, the decision to use mean daily data therefore has advantages and disadvantages. A major advantage is the possibility to analyse the processes from a climatological perspective, which can not be done on the basis of monthly data. But, it is clear that some information is lost by aggregation from hourly to daily data. To test, how sensitive the results are regarding the use of a different significance levels, we repeated the analysis with the significance level 0.01 for the correlation between wind speed in 300 hPa and precipitation (Fig. S8) and compared the results with the results gained using 0.05 as significance level (Fig. 3). The resulting patterns do not change very much. The areas with negative and positive correlations are a little bit smaller, but the changes occur where the values are already lower (at the borders of the correlation patterns). The regions with the highest correlations stay stable and even small areas of positive or negative correlations do not disappear.

The number of precipitation days on which all analysis depends is variable regarding the analysed months and regions, but we assume that the condition of at least 13 precipitation days per grid point, applied for of all days of a specific month during the study period 2001-2013, respectively, ensures a reasonable data basis. Grid points which do not match this criterion are excluded from further analysis.

Since we only look at the first two PCs, it is possible that mechanisms controlling precipitation, which appear in higher PCs, are not considered in this study. The current study is limited to dominant patterns and thereby to the first two PCs, because they together explain more than 60% of the variance of the data. Patterns with lower explained variance and transient patterns will be subject of a subsequent study.

Formatiert: Abstand Vor: 0 Pt., Abstand zwischen Absätzen gleicher Formatierung einfügen, Keine Absatzkontrolle, Leerraum zwischen asiatischem und westlichem Text nicht anpassen, Leerraum zwischen asiatischem Text und Zahlen nicht anpassen

Gelöscht: on

Gelöscht: data process based

Gelöscht: view

Gelöscht: could

Gelöscht: . For example, it is not clear whether

Formatiert: Schriftfarbe: Text 1

Formatiert: Schriftfarbe: Text 1

Formatiert: Schriftfarbe: Text 1

Gelöscht: between the vertical wind speed and precipitation in the PKwH region are caused by a plausible physical process as described in section 3.2.2

Formatiert: Schriftfarbe: Text 1

Gelöscht: by the aggregation from hourly to daily resolution, which could mask out vertical wind speed conditions favourable for precipitation due to information loss

Formatiert: Schriftfarbe: Text 1

Formatiert: Schriftfarbe: Text 1, Deutsch

Gelöscht: In general, when interpreting correlations, one has to keep in mind that correlation not automatically can be interpreted as causality.

Gelöscht: only

Gelöscht: only

Gelöscht: on

5 Conclusion

Gaining a better understanding of the relationship between dynamical variables and precipitation and the underlying processes is important since precipitation is the key element of the hydrological cycle of the TP and surrounding high mountain ranges. Precipitation variability has a large impact on the water availability in the densely populated downstream regions of India, Pakistan and south-east Asia, by directly governing river runoff by precipitation or with a time lag by snow melt.

This study shows that different factors influence precipitation in different regions of the TP and adjacent high mountain ranges during different times of the year and in different ways. For example, the 300 hPa wind speed has a positive effect in the western parts of the study region in winter and spring, while it has a negative effect on precipitation on the TP during summer. This clearly shows that the impact of the mid-latitude westerlies is strong, not only in winter by enhancing moisture advection for orographic and frontal precipitation in the western parts of the study region, but also by cutting of deep convection during summer on the TP and in other regions and seasons where and when precipitation is mainly convective.

The negative effect of high horizontal wind speeds on precipitation plays an important role in regions and seasons which are dominated by convective precipitation e.g. the Tibetan Plateau in summer (Maussion et al. 2014). The positive effect occurs in regions with mainly frontal/cyclonic or orographic precipitation. Precipitation benefits from enhanced moisture transport by strengthened atmospheric flow, especially when the moisture flow is lifted up by orographic forcing. This plays an important role in our study region because of the high mountain ranges surrounding the Tibetan Plateau.

Therefore, the TP and the entire study region can be partitioned by considering the dominant form of precipitation that occurs, cyclonic/frontal or convective precipitation. This enables us to more clearly determine the relevancy/importance of the monsoon system and the mid-latitude westerlies for the precipitation distribution. The classification of precipitation has been determined by cluster analysis and shows a mostly monsoonal influenced class, a convective class, and a hybrid class in between. This highlights that it is not possible to draw an exact distinction for the monsoon extent and that there will always be a relatively broad area between monsoonal influenced precipitation and solely convective dominated precipitation caused by the inter-annual variability of monsoon strength and other factors.

Perhaps it is possible to say that the precipitation on the central TP in summer is influenced by the monsoon system regarding moisture supply, however moisture recycling is also important, and the mid-latitude westerlies act as a control regarding suppression or enhancement of precipitation due to the strong negative effect of high horizontal wind speeds on the development of deep convection.

A next step will analyse the combined effects of precipitation controls, since the current study has shown that the controls are not independent of each other. We intend to use a combination of PCA of the detected dominant patterns and cluster analysis to detect control regimes, as in Forsythe et al. (2015) to obtain a climate classification for the Himalayan arc and its surroundings. These regimes can perhaps help to explain regional features of glacier mass balance, like the so-called Karakoram anomaly (e.g. Hewitt, 2005), or observed lake level changes (e.g. Liu et al., 2010; Zhang et al., 2011), which show a different behaviour compared to the surrounding regions.

Author contribution

Gelöscht:

Gelöscht: dynamic

Gelöscht: controls

Gelöscht: and

Gelöscht: great

Gelöscht: , e.g.

Gelöscht: directly

Gelöscht: and

Gelöscht: , and sometimes even have an exactly opposite effect.

Gelöscht: wind speed at the

Gelöscht: level

[4] verschoben

Gelöscht: divided regarding

Gelöscht: realise

Gelöscht: precipitation

Gelöscht: emerged

Gelöscht: illustrates

Gelöscht: border

Gelöscht: border

Gelöscht: /region

Gelöscht:

Gelöscht: Maybe one can

Gelöscht: nevertheless

Gelöscht: but that

Gelöscht: whether

Gelöscht: development is possible or not due

Gelöscht: In a

Gelöscht: we

Gelöscht: again showed

Gelöscht: from

Gelöscht: like

Gelöscht: did

Gelöscht: maybe

Gelöscht: Liu et al., 2010; Zhang et al., 2011)

J. Curio and D. Scherer designed the study and discussed all results. J. Curio carried out the analyses and prepared the manuscript with contribution from D. Scherer.

Acknowledgements

This work was supported by the German Federal Ministry of Education and Research (BMBF) Programme “Central Asia – Monsoon Dynamics and Geo-Ecosystems” (CAME) within the WET project (“Variability and Trends in Water Balance Components of Benchmark Drainage Basins on the Tibetan Plateau”) under the code 03G0804A and by the German Research Foundation (DFG) Priority Programme 1372, “Tibetan Plateau: Formation – Climate – Ecosystems” within the DynRG-TiP (“Dynamic Response of Glaciers on the Tibetan Plateau to Climate Change”) project under the codes SCHE 750/4-1, SCHE750/4-2, SCHE 750/4-3. We would like to thank the four anonymous referees for their thoughtful comments, critiques, and suggestions on an earlier version of this manuscript.

References

Araguás-Araguás, L and F. K (1998). Stable isotope composition of precipitation over southeast Asia. *Journal of Geophysical Research*, *103* Retrieved from http://onlinelibrary.wiley.com/doi/10.1029/98JD02582/full

Back, L. E., & Bretherton, C. S (2005). The relationship between wind speed and precipitation in the Pacific ITCZ. *Journal of Climate*, *18*(20), 4317–4328. doi:10.1175/JCLI3519.1

Barros, A. P., Chiao, S., Lang, T. J., Burbank, D., & Putkonen, J. (2006). From weather to climate—Seasonal and interannual variability of storms and implications for erosion processes in the Himalaya. *Geological Society of America Special Papers*, *398*(02), 17 – 38. doi:10.1130/2006.2398(02).

Bartholy, J., & Pongracz, R. (2010). Analysis of precipitation conditions for the Carpathian Basin based on extreme indices in the 20th century and climate simulations for 2050 and 2100. *Physics and Chemistry of the Earth*, *35*(1-2), 43– 51. doi:10.1016/j.pce.2010.03.011

Bothe, O., Fraedrich, K., & Zhu, X (2009). The large-scale circulations and summer drought and wetness on the Tibetan plateau. *International Journal of Climatology*, *855*(May 2009), n/a–n/a. doi:10.1002/joc.1946

Cannon, F., Carvalho, L. M. V., Jones, C., & Bookhagen, B (2014). Multi-annual variations in winter westerly disturbance activity affecting the Himalaya. *Climate Dynamics*, *44*(1-2), 441–455. doi:10.1007/s00382-014-2248-8

Chen, B., Xu, X.-D., Yang, S., & Zhang, W (2012). On the origin and destination of atmospheric moisture and air mass over the Tibetan Plateau. *Theoretical and Applied Climatology*, *110*(3), 423–435. doi:10.1007/s00704-012-0641-y

Curio, J., Maussion, F., & Scherer, D (2015). A twelve-year high-resolution climatology of atmospheric water transport over the Tibetan Plateau. *Earth System Dynamics*, *6*, 109–124. doi:10.5194/esd-6-109-2015

Dimri, A. P., Niyogi, D., Barros, A. P., Ridley, J., Mohanty, U. C., Yasunari, T., & Sikka, D. R. (2015). Western Disturbances: A review. doi:10.1002/2014RG000460

Findell, K. L. (2003). Atmospheric controls on soil moisture-boundary layer interactions: Three-dimensional wind effects. *Journal of Geophysical Research*, *108*, 1–21.

Gelöscht:
Gelöscht: ., Froehlich,
Gelöscht: ., Rozanski, K.:
Gelöscht: J. Geophys. Res.,
Formatiert: Schriftart:Kursiv
Gelöscht: , 28721–28742,
Gelöscht: :
Gelöscht: , 1998.
Gelöscht: and
Gelöscht: .:
Formatiert: Schriftart:Kursiv
Formatiert: Schriftart:Kursiv
Gelöscht: , 2005.
Formatiert: Einzug: Links: 0 cm, Hängend: 0,75 cm
Gelöscht: and
Gelöscht: .:
Formatiert: Schriftart:Kursiv
Gelöscht: 30, 844–
Formatiert: Schriftart:Kursiv
Gelöscht: ,
Gelöscht: , 2009.
Gelöscht: and
Gelöscht: .:
Formatiert: Schriftart:Kursiv
Formatiert: Schriftart:Kursiv
Gelöscht: , 2014.
Gelöscht: and
Gelöscht: .:
Formatiert: Schriftart:Kursiv
Formatiert: Schriftart:Kursiv
Gelöscht: , 2012.
Gelöscht: .:
Formatiert: Schriftart:Kursiv
Formatiert: Schriftart:Kursiv
Gelöscht: , 2015.

doi:10.1029/2001JD001515

Forsythe, N., Blenkinsop, S., & Fowler, H. J. . (2015). Exploring objective climate classification for the Himalayan arc and adjacent regions using gridded data sources. *Earth System Dynamics*, *6*(1), 311–326. doi:10.5194/esd-6-311-2015

Frei, C., Schär, C., Lüthi, D., & Davies, H. C. (1998). Heavy precipitation processes in a warmer climate. *Geophysical Research Letters*, *25*(9), 1431. doi:10.1029/98GL51099

Garreaud, R. D. (2007). Precipitation and circulation covariability in the extratropics. *Journal of Climate*, *20*(18), 4789–4797. doi:10.1175/JCLI4257.1

Giovannettone, J, P., & Barros, A. P. (2009). Probing Regional Orographic Controls of Precipitation and Cloudiness in the Central Andes Using Satellite Data. *Journal of Hydrometeorology*, *10*(1), 167–182. doi:10.1175/2008JHM973.1

Hahn, D., & Manabe, S. (1975). The role of mountains in the south Asian monsoon circulation. *Journal of the Atmospheric Sciences*, 32, 1515-1541.

Hewitt, K. (2005). The Karakoram anomaly? Glacier expansion and the'elevation effect,'Karakoram Himalaya. *Mountain Research and Development*, *25*(4), 332–340, doi: 10.1659/0276-4741(2005)025[0332:TKAGEA]2.0.CO;2

Hren, M. T., Bookhagen, B., Blisniuk, P. M., Booth, A. L., & Chamberlain, C. P. (2009). δ18O and δD of streamwaters across the Himalaya and Tibetan Plateau: Implications for moisture sources and paleoelevation reconstructions. *Earth and Planetary Science Letters*, *288*(1-2), 20–32. doi:10.1016/j.epsl.2009.08.041

Johansson, B., & Chen, D. (2003). The influence of wind and topography on precipitation distribution in Sweden: Statistical analysis and modelling. *International Journal of Climatology*. doi:10.1002/joc.951

Joswiak, D. R., Yao, T., Wu, G., Tian, L., & Xu, B. (2013). Ice-core evidence of westerly and monsoon moisture contributions in the central Tibetan Plateau. *Journal of Glaciology*, *59*(213), 56–66. doi:10.3189/2013JoG12J035

Kurita, N., & Yamada, H. (2008). The Role of Local Moisture Recycling Evaluated Using Stable Isotope Data from over the Middle of the Tibetan Plateau during the Monsoon Season. *Journal of Hydrometeorology*, *9*(4), 760–775. doi:10.1175/2007JHM945.1

Liu, B., Xu, M., & Henderson, M. (2011). Where have all the showers gone? Regional declines in light precipitation events in China, 1960-2000. *International Journal of Climatology*, *31*(8), 1177–1191. doi:10.1002/joc.2144

Liu, J., Kang, S., Gong, T., & Lu, a. (2010). Growth of a high-elevation large inland lake, associated with climate change and permafrost degradation in Tibet. *Hydrology and Earth System Sciences*, *14*(3), 481–489. doi:10.5194/hess-14-481-2010

Liu, W., Wang, L., Chen, D., Tu, K., Ruan, C., & Hu, Z. (2015). Large-scale circulation classification and its links to observed precipitation in the eastern and central Tibetan Plateau. *Climate Dynamics*, (AUGUST). doi:10.1007/s00382-015-2782-z

Liu, X., & Yin, Z.-Y. (2001). Spatial and Temporal Variation of Summer Precipitation over the Eastern Tibetan Plateau and the North Atlantic Oscillation. *Journal of Climate*, *14*(13), 2896–2909. doi:10.1175/1520-0442(2001)014<2896:SATVOS>2.0.CO;2

Maussion, F., Scherer, D., Finkelnburg, R., Richters, J., Yang, W., & Yao, T. (2011). WRF simulation of a precipitation event over the Tibetan Plateau, China – an assessment using remote sensing and ground observations. *Hydrology and Earth System Sciences*, *15*(6), 1795–1817. doi:10.5194/hess-15-1795-2011

Gelöscht: and… Fowler, H. J.: ... [31]
Formatiert ... [32]
Gelöscht: , 2015.
Formatiert ... [33]
Gelöscht: .:
Formatiert ... [34]
Gelöscht: , 2007.
Gelöscht: Gentine,
Formatiert ... [40]
Formatiert ... [35]
Formatiert ... [36]
Gelöscht: Holtslag
Formatiert ... [37]
Gelöscht: a. M., D'Andrea, F., and Ek, M.: Surfac ... [38]
Formatiert ... [39]
Gelöscht: on the Onset
Gelöscht: Moist Convection over Land.
Formatiert ... [41]
Gelöscht: 14(5), 1443–1462.
Formatiert ... [42]
Gelöscht: JHM-D-12-0137.1, 2013.
Gelöscht: .:
Formatiert ... [43]
Gelöscht: . doi: ... [44]
Gelöscht: .:
Formatiert ... [45]
Gelöscht: http://dx.doi.org/…0.1659/0276- ... [46]
Gelöscht: and… Chamberlain, C. P.: ... [47]
Formatiert ... [48]
Gelöscht: , 2009.
Gelöscht: Janjic, Z. I.: Nonsingular Implementatio ... [49]
Gelöscht: and… Xu, B.: ... [50]
Formatiert ... [51]
Gelöscht: , 2013.
Formatiert ... [52]
Gelöscht: and… Yamada, H.: ... [53]
Formatiert ... [54]
Gelöscht: , 2008.
Formatiert ... [55]
Gelöscht: and… Lu, A.: ... [56]
Formatiert ... [57]
Gelöscht: , 2010.
Gelöscht: and… Hu, Z.: ... [58]
Formatiert ... [59]
Gelöscht: , 2015.
Gelöscht: .:
Formatiert ... [60]
Gelöscht: , 2001.
Gelöscht: Ma, Y., Wang, Y., Wu, R., Hu, Z., Yang ... [61]
Formatiert ... [62]
Gelöscht: , 2011.

Maussion, F., Scherer, D., Mölg, T., Collier, E., Curio, J., & Finkelnburg, R. (2014). Precipitation Seasonality and Variability over the Tibetan Plateau as Resolved by the High Asia Reanalysis*. *Journal of Climate*, *27*(5), 1910–1927. doi:10.1175/JCLI-D-13-00282.1

Mölg, T., & Chiang, J. (2009). Temporal precipitation variability versus altitude on a tropical high mountain: Observations and mesoscale atmospheric modelling. *Quarterly Journal of the Royal Meteorological Society*, *135*, 1439–1455. doi:10.1002/qj.461

Mölg, T., Maussion, F., & Scherer, D. (2014). Mid-latitude westerlies as a driver of glacier variability in monsoonal High Asia. *Nature Climate Change*, *4*(1), 68–73. doi:10.1038/nclimate2055

Polade, S. D., Pierce, D. W., Cayan, D. R., Gershunov, A., & Dettinger, M. D. (2014). The key role of dry days in changing regional climate and precipitation regimes. *Scientific Reports*, *4*(4364), 8pp. doi:10.1038/srep04364

Roe, G. H. (2005). Orographic Precipitation. *Annual Review of Earth and Planetary Sciences*, *33*(1), 645–671. doi:10.1146/annurev.earth.33.092203.122541

Rose, B. E. J., & Lin, C. A. (2003). Precipitation from vertical motion: A statistical diagnostic scheme. *International Journal of Climatology*, *23*(8), 903–919. doi:10.1002/joc.919

Rüthrich, F. (2015). Lake-Related Cloud Dynamics on the Tibetan Plateau: Spatial Patterns and Interannual Variability. *Journal of Climate*, *28*, 9080-910. doi: 10.1175/JCLI-D-14-00698.1

Schiemann, R., & Lüthi, D. (2008). The precipitation climate of Central Asia—intercomparison of observational and numerical data sources in a remote semiarid region. *International Journal of Climatology*, 28, 295–314. doi:10.1002/joc.1532

Schiemann, R., Lüthi, D., & Schär, C. (2009). Seasonality and Interannual Variability of the Westerly Jet in the Tibetan Plateau Region*. *Journal of Climate*, *22*(11), 2940–2957. doi:10.1175/2008JCLI2625.1

Shinker, J. J., Bartlein, P. J., & Shuman, B. (2006). Synoptic and dynamic climate controls of North American mid-continental aridity. *Quaternary Science Reviews*, *25*(13-14), 1401–1417. doi:10.1016/j.quascirev.2005.12.012

Skamarock, W., & Klemp, J. (2008). A time-split nonhydrostatic atmospheric model for weather research and forecasting applications. *Journal of Computational Physics*, *227*(7), 3465–3485. doi:10.1016/j.jcp.2007.01.037

Spiess, M., Schneider, C., & Maussion, F. (2015). MODIS-derived interannual variability of the equilibrium-line altitude across the Tibetan Plateau. *Annals of Glaciology*, *57*(71), 140–154. doi:10.3189/2016AoG71A014

Tian, L., Yao, T., MacClune, K., White, J. W. C., Schilla, a., Vaughn, B., ... Ichiyanagi, K. (2007). Stable isotopic variations in west China: A consideration of moisture sources. *Journal of Geophysical Research*, *112*(D10), D10112. doi:10.1029/2006JD007718

Trenberth, K. E. (1999). Atmospheric Moisture Recycling: Role of Advection and Local Evaporation. *Journal of Climate*, *12*(5), 1368–1381. doi:10.1175/1520-0442(1999)012<1368:AMRROA>2.0.CO;2

Webster, P., Magana, V., & Palmer, T. (1998). Monsoons: Processes, predictability, and the prospects for prediction. *Journal of Geophysical Research*, *103*(C7), 14451-14510.

Xu, X., Lu, C., Shi, X., & Gao, S. (2008). World water tower: An atmospheric perspective. *Geophysical Research Letters*, 35, L20815, doi: 10.1029/2008GL035867

Yang, K., Wu, H., Qin, J., Lin, C., Tang, W., & Chen, Y. (2014). Recent climate changes over

Gelöscht: .:

Gelöscht: , 2014.

Formatiert: Schriftart:Kursiv

Gelöscht: Medeiros, B., Hall, A., & Stevens, B.: What controls the mean depth of the PBL? Journal of Climate, 18(16), 3157–3172. doi:10.1175/JCLI3417.1, 2005. ... [63]

Formatiert: Schriftart:Kursiv

Gelöscht: , 1439–1455… doi:10.1002/qj, 2009. ... [64]

Gelöscht: and… Scherer, D.: ... [65]

Formatiert: Schriftart:Kursiv

Gelöscht: , 2013.

Gelöscht: Patil, M. N., Patil, S. D., Waghmare, R. T., & Dharmaraj, T.: Planetary Boundary Layer height over the Indian subcontinent during extreme monsoon years. *Journal of Atmospheric and Solar-Terrestrial Physics*, *92*, 94–99. doi:10.1016/j.jastp.2012.10.011, 2013.

Formatiert: Blocksatz, Abstand Vor: 5 Pt.

Gelöscht: ., Reudenbach, C., Thies, B., and Bendix, J.:… (2015). Lake-Related Cloud Dynamics on the Tibetan Plateau: Spatial Patterns and Interannual Variability. ... [66]

Formatiert ... [67]

Gelöscht: –9104.doi: http://dx.doi.org/10.1175/JCLI-D-14-00698.1, 2015.

Gelöscht: and… Lüthi, D.:… (2008). The precipitation climate of Central Asia—intercomparison of observ ... [68]

Gelöscht: and… Schär, C.: ... [69]

Formatiert ... [70]

Gelöscht: , 2009.

Gelöscht: and… Shuman, B.: ... [71]

Formatiert ... [72]

Gelöscht: , 2006.

Gelöscht: and… Klemp, J.: ... [73]

Formatiert: Schriftart:Kursiv

Gelöscht: , 2008.

Gelöscht: and… Maussion, F.:. ... [74]

Formatiert ... [75]

Gelöscht: , 2015.

Gelöscht: A

Formatiert: Schriftart:Times New Roman

Gelöscht: Vachon, R., and… Ichiyanagi, K.: ... [76]

Gelöscht: ,… doi:10.1029/2006JD007718, 2007. ... [78]

Formatiert ... [77]

Gelöscht: .:

Formatiert ... [79]

Gelöscht: , 1999.

Gelöscht: N., Shukla, J., Tomas, R. A., Yanai, M., ... [80]

Formatiert: Schriftart:Kursiv

Gelöscht: ,…*(C7)*, 14451-14510, doi:10.1029/97J ... [81]

Gelöscht: Wilks, D. S.: Statistical Methods in the ... [82]

Gelöscht: Yang, K., Koike, T., Fujii, H., Tamura, ... [83]

the Tibetan Plateau and their impacts on energy and water cycle: A review. *Global and Planetary Change*, *112*, 79–91. doi:10.1016/j.gloplacha.2013.12.001

Zhang, J. W., & Atkinson, B. W. (1995). Stability and wind shear effects on meso-scale cellular convection. *Boundary-Layer Meteorology*, *75*(3), 263–285. doi:10.1007/BF00712697

Zhang, G., Xie, H., Kang, S., Yi, D., & Ackley, S. F. (2011). Monitoring lake level changes on the Tibetan Plateau using ICESat altimetry data (2003-2009). *Remote Sensing of Environment*, *115*(7), 1733–1742. doi:10.1016/j.rse.2011.03.005

Formatiert: Schriftart:Kursiv

Gelöscht: , 2014.

Formatiert: Schriftart:Kursiv

Gelöscht: and

Gelöscht: .:

Formatiert: Schriftart:Kursiv

Gelöscht: , 2011.

Formatiert: Schriftart:Kursiv

Formatiert: Blocksatz

Gelöscht: ... [84]

Figures

Formatiert: Blocksatz

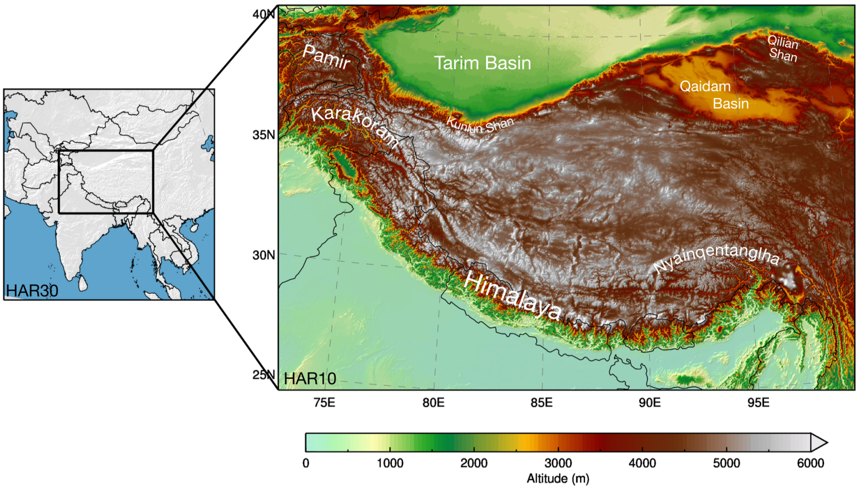
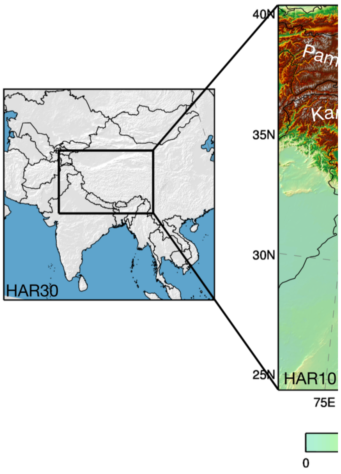


Fig. 1: Map of the Weather and Research Forecasting (WRF) model domain HAR10 (high Asia domain) and its location nested in the larger domain HAR30 (south-central Asia domain). Geographical locations are indicated in white.

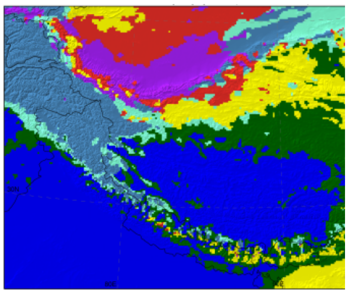


Gelöscht:

Formatiert: Schriftart:(Standard) Times New Roman

Formatiert: Schriftart:(Standard) Times New Roman

Formatiert: Standard, Blocksatz



Gelöscht:

Formatiert: Schriftart:(Standard) Times New Roman

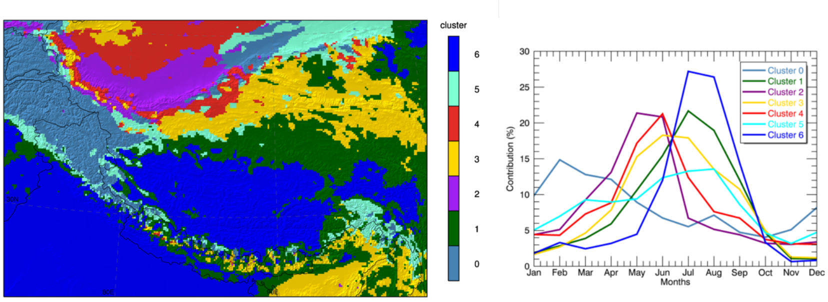


Fig. 2: Precipitation cluster (left) and the mean annual cycle of percentage contribution of monthly precipitation to annual precipitation for each cluster (right).

Formatiert: Schriftart:(Standard) Times New Roman

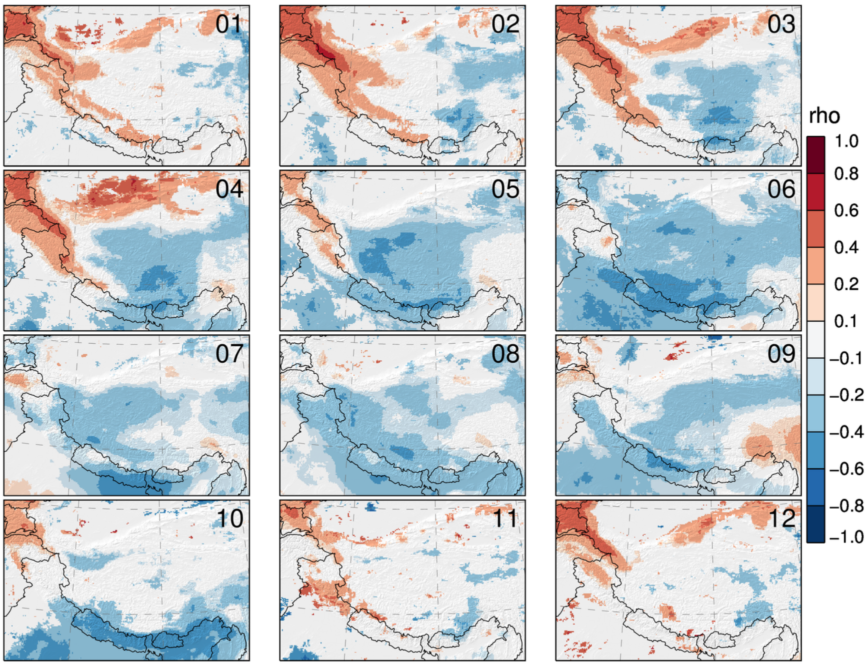


Figure 3. Coefficient of correlation (rho) between horizontal wind speed at 300 hPa (WS300) and precipitation for all months (01-12). Positive correlations are denoted in red, while negative correlations are denoted in blue.

Gelöscht: ... [85]

Formatiert: Schriftart:(Standard) Times New Roman

Formatiert: Deutsch

Gelöscht: :

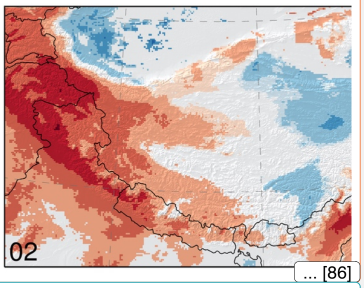
Formatiert: Schriftart:+Designkörper (Calibri), Deutsch

Formatiert: Standard, Blocksatz

Gelöscht: February (02), April (04), and June (06).

Formatiert: Schriftart:+Designkörper (Calibri), Deutsch

Gelöscht:



... [86]

Formatiert: Schriftart:(Standard) Times New Roman

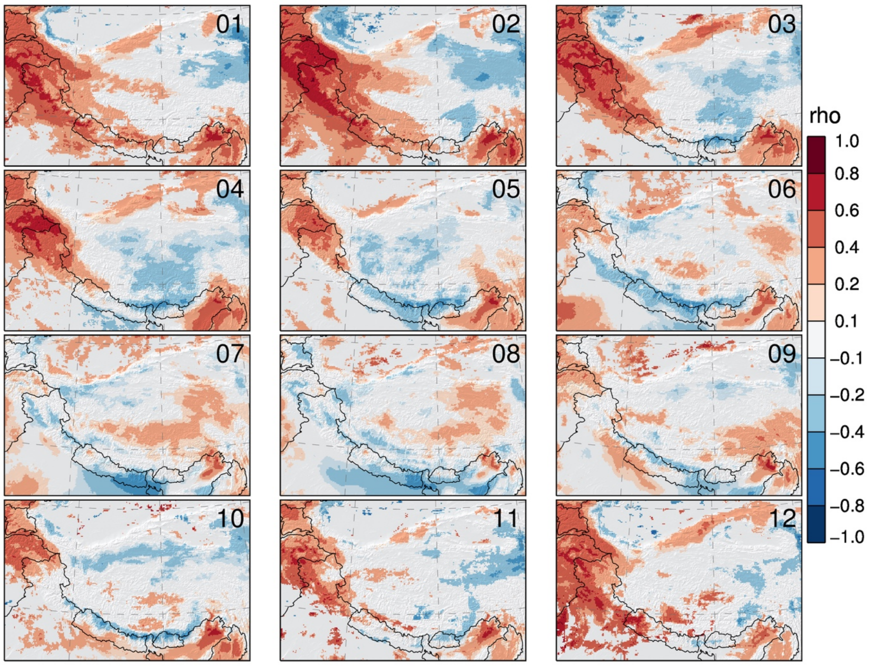


Figure 4. Coefficient of correlation (rho) between horizontal wind speed at model level 10 (WS10) and precipitation for all months (01-12). Positive correlations are denoted in red, while negative correlations are denoted in blue.

Formatiert: Schriftart:10 pt, Schriftfarbe: Text 1, Deutsch, Erweitert um 0,75 Pt.

Gelöscht: :

Formatiert: Schriftart:Arial, 10 pt, Schriftfarbe: Text 1, Deutsch, Erweitert um 0,75 Pt.

Formatiert: Standard, Blocksatz

Gelöscht: February (02) and July (07). Positive correlations are denoted in red, while negative correlations are denoted in blue. ... [87]

Formatiert: Schriftart:(Standard) Times New Roman

Formatiert: Schriftart:+Designkörper (Calibri), Deutsch

Gelöscht: ... [88]

Formatiert: Schriftart:(Standard) Times New Roman

[6] nach unten: Fig. 6: Mean vertical wind speed at 300 hPa for January (01) and July (07). ... [89]

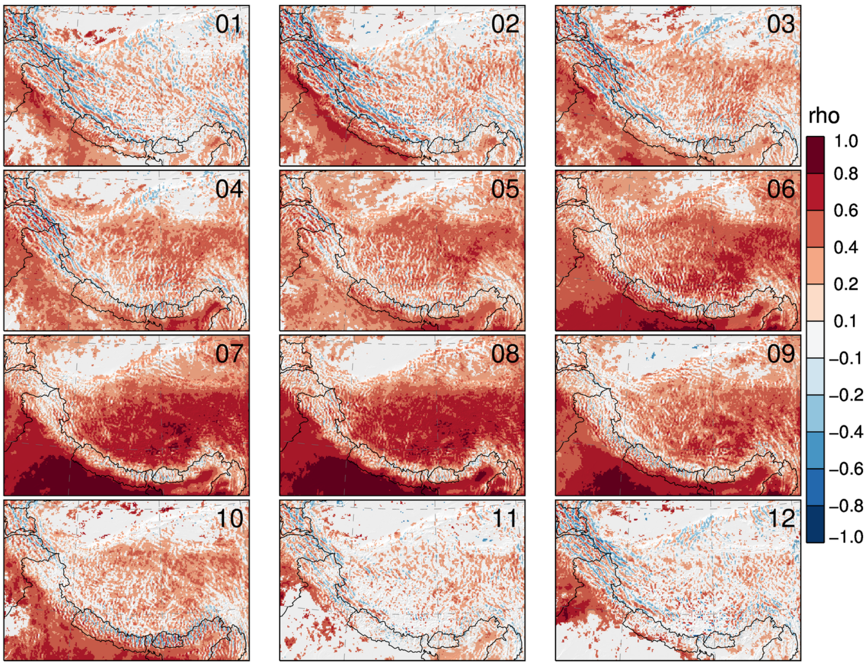
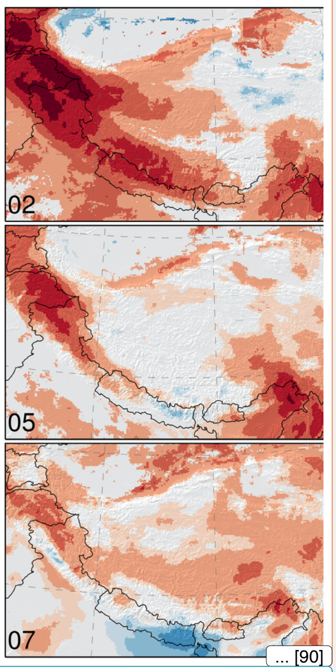


Figure 5. Coefficient of correlation (rho) between vertical wind speed at 300 hPa (WS300) and precipitation for all months (01-12). Positive correlations are denoted in red, while negative correlations are denoted in blue.



Gelöscht: ... [90]

Formatiert: Schriftart:(Standard) Times New Roman

Formatiert: Schriftart:+Designkörper (Calibri), Deutsch

Gelöscht: column integrated atmospheric water transport (AWT

Formatiert: Standard, Blocksatz

Gelöscht: February (02), May (05), and July (07

Formatiert: Schriftart:+Designkörper (Calibri), Deutsch

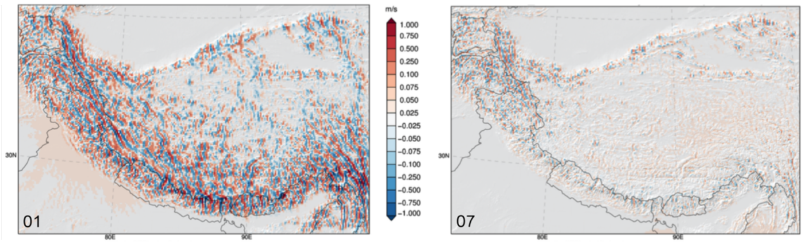


Fig. 6: Mean vertical wind speed at 300 hPa for January (01) and July (07).

Formatiert: Schriftart:(Standard) Times New Roman

[6] verschoben

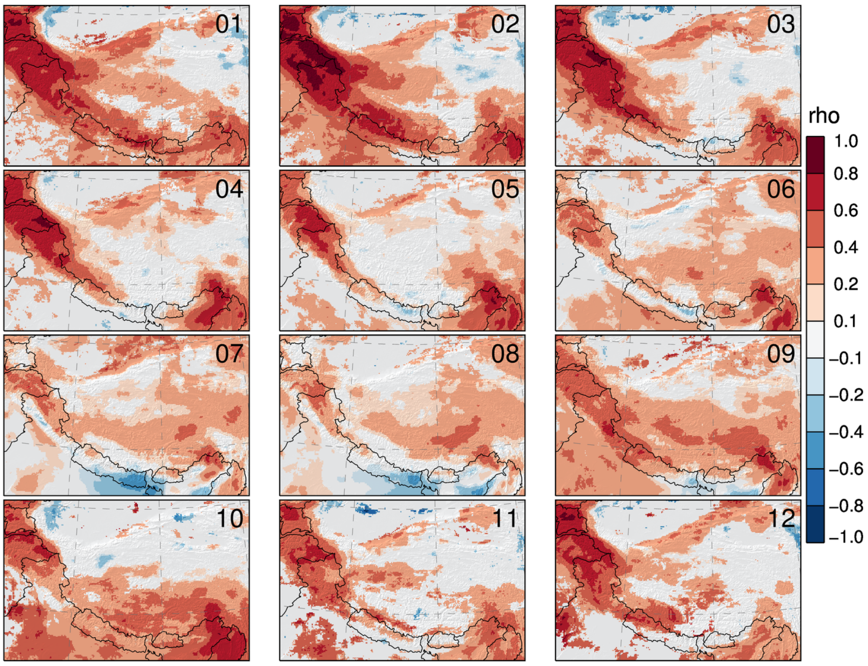
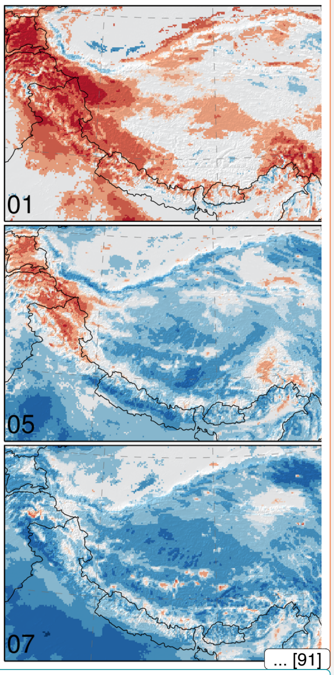


Figure 7. Coefficient of correlation (rho) between atmospheric water transport (AWT) and precipitation for all months (01-12). Positive correlations are denoted in red, while negative correlations are denoted in blue.

Gelöscht:



... [91]

Formatiert: Schriftart:(Standard) Times New Roman

Formatiert: Schriftart:+Designkörper (Calibri), Deutsch

Gelöscht: planetary boundary layer height (PBLH

Formatiert: Standard, Blocksatz

Gelöscht: January

Gelöscht:), May (05), and July (07

Formatiert: Schriftart:+Designkörper (Calibri), Deutsch

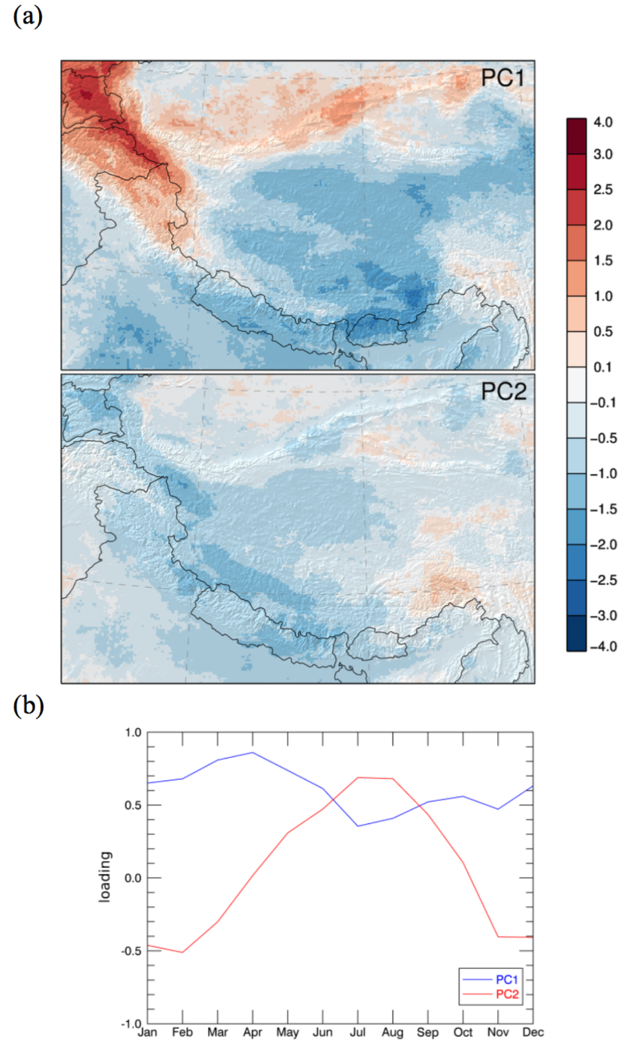
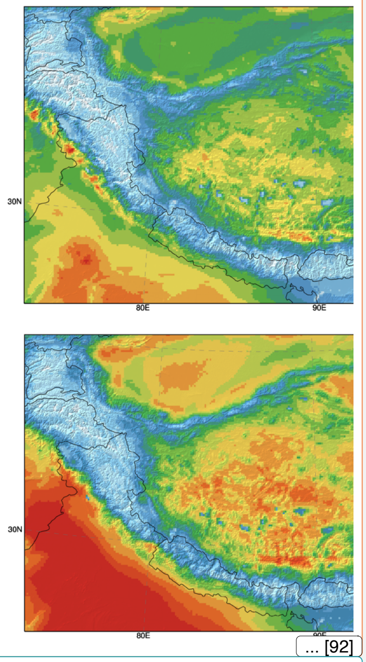


Figure 8. Scores of first two principal components PC1 and PC2 for the correlation between horizontal wind speed at 300 hPa (WS300) and precipitation **(a)** (positive values are denoted in red, while negative values are denoted in blue) and the monthly loadings **(b)** for both PCs.



Gelöscht: ... [92]

Formatiert: Schriftart:(Standard) Times New Roman

Formatiert: Schriftart:(Standard) Times New Roman

Formatiert: Schriftart:(Standard) Times New Roman

Formatiert: Schriftart:(Standard) Times New Roman

Gelöscht: 10

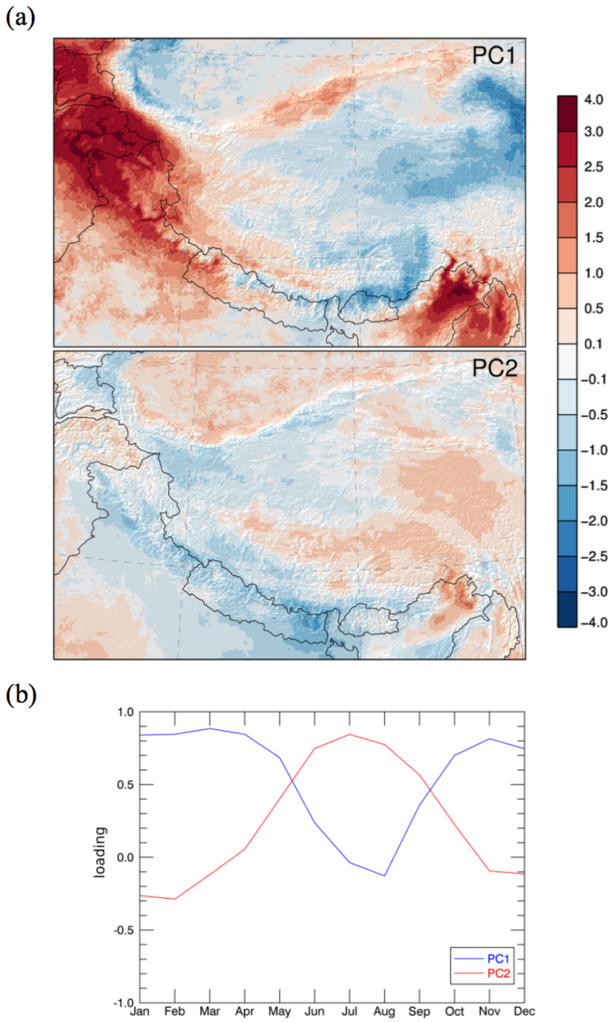


Figure 9. Scores of first two principal components PC1 and PC2 for the correlation between horizontal wind speed at model level 10 (WS10) and precipitation **(a)** (positive values are denoted in red, while negative values are denoted in blue) and the monthly loadings **(b)** for both PCs.

Gelöscht: ... [93]

Formatiert: Schriftart:(Standard) Times New Roman

Formatiert: Schriftart:(Standard) Times New Roman

Formatiert: Schriftart:(Standard) Times New Roman

Gelöscht: 11

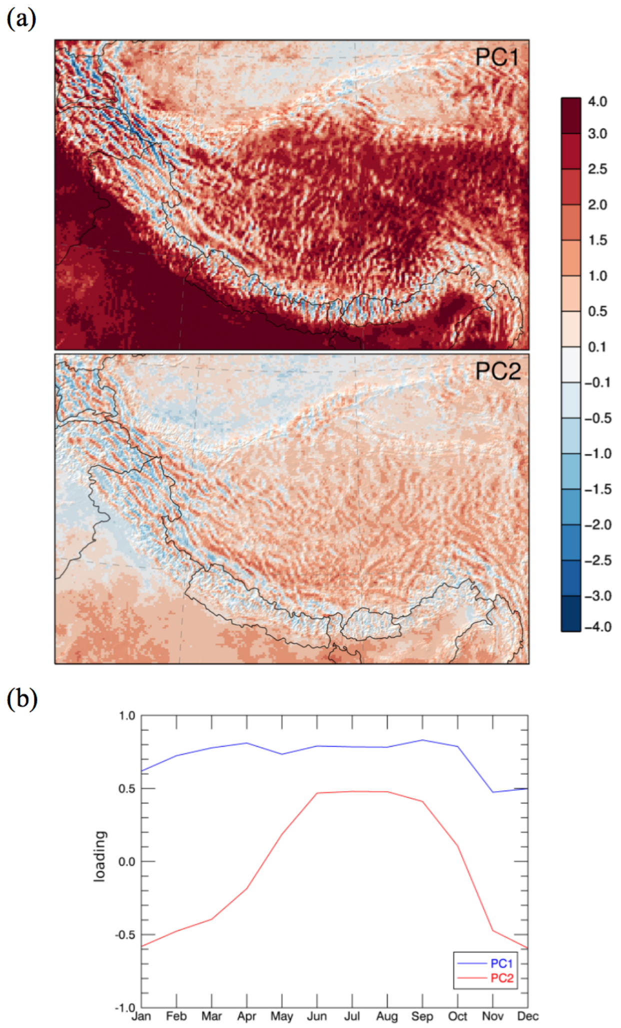


Figure 10. Scores of first two principal components PC1 and PC2 for the correlation between vertical wind speed at 300 hPa (W300) and precipitation **(a)** (positive values are denoted in red, while negative values are denoted in blue) and the monthly loadings **(b)** for both PCs.

Gelöscht: ... [94]

Formatiert: Schriftart:(Standard) Times New Roman

Formatiert: Schriftart:(Standard) Times New Roman

Formatiert: Schriftart:(Standard) Times New Roman

Gelöscht: 12

Formatiert: Schriftart:Times New Roman, 12 pt

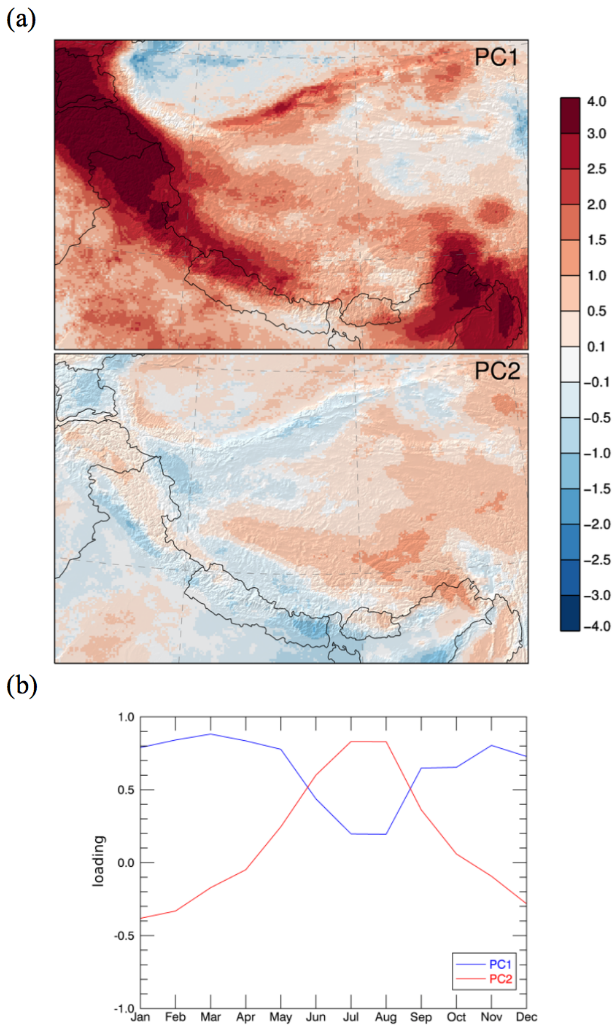


Figure 11. Scores of first two principal components PC1 and PC2 for the correlation between atmospheric water transport (AWT) and precipitation **(a)** (positive values are denoted in red, while negative values are denoted in blue) and the monthly loadings **(b)** for both PCs.

Gelöscht: ... [95]

Formatiert: Schriftart:(Standard) Times New Roman

Formatiert: Schriftart:(Standard) Times New Roman

Formatiert: Schriftart:(Standard) Times New Roman

Gelöscht: 13

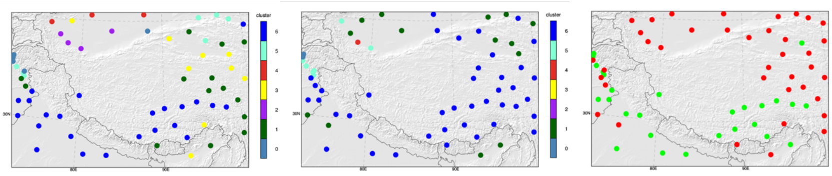


Figure 12. Map of precipitation cluster for HAR10 grid points (left) and the associated NCDC stations (middle). The map on the right shows whether the cluster match (green dots) or not (red dots).

Gelöscht: ... [96]

Formatiert: Schriftart:(Standard) Times New Roman

Formatiert: Schriftart:(Standard) Times New Roman

Formatiert: Schriftart:(Standard) Times New Roman

Tables

cluster		NCDC						
		0	1	2	3	4	5	6
HAR	0	40 %	0 %	0 %	0 %	0 %	40 %	20 %
	1	0 %	14.3 %	0 %	0 %	0 %	0 %	85.7 %
	2	0 %	50 %	0 %	0 %	25 %	25 %	0 %
	3	0 %	33.3 %	0 %	0 %	0 %	0 %	66.6 %
	4	0 %	33.3 %	0 %	0 %	0 %	33.3 %	33.3 %
	5	0 %	43 %	0 %	0 %	0 %	43 %	14 %
	6	0 %	13 %	0 %	0 %	0 %	0 %	87 %

Table 1. The percentage of NCDC stations falling in each of the seven possible HAR cluster. 100% would mean that all NCDC stations falls in the same cluster as the nearest HAR grid point.

Seite 1: [1] Gelöscht **Julia Curio** **01.08.16 23:13**

There are many studies on the influence of atmospheric circulation modes, e.g. the North Atlantic Oscillation, the Arctic Oscillation, and El Nino/Southern Oscillation, on climate and precipitation in high Asia and on the monsoon systems (e.g. Bothe et al., 2009; Liu et al., 2015; Liu and Yin, 2001; Rüthrich et al., 2015). Less attention is drawn to the underlying processes controlling precipitation development on the TP and the surrounding high mountain ranges. Using the

Seite 2: [2] Gelöscht **Julia Curio** **01.08.16 23:13**

Therefore, we want to examine which precipitation controls has where and when an

Seite 2: [3] Auf Seite 4 verschoben (Verschiebung Nr. 2) **Julia Curio** **01.08.16 23:13**

The selection of precipitation controls relies on well studied relations of these factors with precipitation (e.g.

Seite 2: [4] Gelöscht **Julia Curio** **01.08.16 23:13**

Back and Bretherton, 2005; Garreaud, 2007; Shinker et al., 2006) but these controls were not investigated at high spatial and temporal resolution in high mountain Asia until now.

Seite 2: [5] Auf Seite 2 verschoben (Verschiebung Nr. 1) **Julia Curio** **01.08.16 23:13**

The different precipitation controls have effects on different spatial scales.

Seite 2: [6] Gelöscht **Julia Curio** **01.08.16 23:13**

While the horizontal and vertical wind speed at 300 hPa are large-scale controls, their counter parts in the boundary layer and the PBLH are active on the meso-scale. The AWT connects the large- with the meso-scale because it is effective on both scales and across large distances.

Seite 2: [7] Gelöscht **Julia Curio** **01.08.16 23:13**

with low horizontal wind speeds. On the other hand, high wind speeds enhance moisture advection and thereby strengthen frontal/cyclonic precipitation and also orographic precipitation. At the 300 hPa level we are already in a height where the westerly jet occurs, which strength and location influences the hydro-climate of the TP and central Asia (e.g. Schiemann et al., 2009).

Seite 2: [8] Gelöscht **Julia Curio** **01.08.16 23:13**

Higher horizontal wind speeds in the planetary boundary layer can hinder convection and advect air masses/moisture like its counterpart at 300 hPa, but also can enhance evapotranspiration from the surface (Back & Bretherton, 2005) and therefore convection, depending on the available moisture at the surface. This process is interesting mostly during the warm half of the year, when surface moisture from local sources like lakes, soil moisture, the active layer of permafrost, snow and glacier melt is available. Moisture recycling plays an important role for precipitation on the TP (e.g. Araguás-Araguás et al., 1998; Trenberth, 1999)

Seite 2: [9] Auf Seite 2 verschoben (Verschiebung Nr. 3) **Julia Curio** **01.08.16 23:13**

, on average more than 60% of moisture needed for precipitation falling on the inner TP are provided by the TP itself (Curio et al., 2015).

Seite 2: [10] Gelöscht **Julia Curio** **01.08.16 23:13**

Back and Bretherton (2005) found that there is a relation between near surface wind speed and precipitation in the Pacific ITCZ. Higher wind speeds can intensify the evapotranspiration rate and therefore the development of deep convection.

Seite 2: [11] Formatiert **Julia Curio** **01.08.16 23:13**

Abstand Vor: 0 Pt., Abstand zwischen Absätzen gleicher Formatierung einfügen, Keine Absatzkontrolle, Leerraum zwischen asiatischem und westlichem Text nicht anpassen, Leerraum zwischen asiatischem Text und Zahlen nicht anpassen

Seite 2: [12] Auf Seite 13 verschoben (Verschiebung Nr. 4) **Julia Curio** **01.08.16 23:13**

The negative effect of high horizontal wind speeds on precipitation plays an important role in regions and seasons which are dominated by convective precipitation e.g. the Tibetan Plateau in summer (Maussion et al. 2014).

Seite 2: [13] Gelöscht **Julia Curio** **01.08.16 23:13**

While the positive effect occurs in regions with mainly frontal/cyclonic precipitation because the moisture transport towards these regions is enhanced by the strengthened atmospheric flow.

Seite 3: [14] Gelöscht **Julia Curio** **01.08.16 23:13**

The height of the planetary boundary layer (PBLH) shows the turbulent mixing of the lower atmosphere. It is influenced by solar forcing, turbulent processes, convective activity (Yang et al., 2004), moisture content and temperature of surface and air, and wind speed. Gentine et al. (2013) point out that dry soil surface accelerates the growth of the PBL. The TP has one of the highest PBLs in the world, due to its high altitude and strong solar forcing, but the TP PBL is not fully understood yet because there are only few observations. During daytime in spring and summer the PBL is higher than in the other seasons in this region (Patil et al., 2013) and can exceed heights of 3000 m or more (Ma et al., 2009; Yang et al., 2004) in some regions on the TP due to strong solar forcing and convective activity. The horizontal wind speed influences the PBLH by facilitating the mixing of the atmosphere and the entrainment of air from above the PBL. The PBLH is not a pure dynamic precipitation control, but entrainment as a dynamic factor has great impact on PBLH (Medeiros et al., 2005; Gentine et al., 2013). Additionally, in the HAR the PBLH is determined dynamically by using the Mellor–Yamada–Janjic turbulent kinetic energy scheme (Janjic, 2002) for PBL parameterisation.

The objectives of the current study are two-fold:
i.

Seite 3: [15] Formatiert **Julia Curio** **01.08.16 23:13**

Einzug: Links: 0 cm, Erste Zeile: 0 cm, Abstand Vor: 0 Pt., Nach: 6 Pt., Keine Absatzkontrolle, Leerraum zwischen asiatischem und westlichem Text nicht anpassen, Leerraum zwischen asiatischem Text und Zahlen nicht anpassen

Seite 3: [16] Gelöscht	**Julia Curio**	**01.08.16 23:13**

controls on precipitation development spatially and temporally differentiated, where and when has which precipitation control a how strong influence,

Seite 3: [17] Formatiert	**Julia Curio**	**01.08.16 23:13**

Schriftart:Times, Schriftfarbe: Text 1, Deutsch

Seite 3: [18] Gelöscht	**Julia Curio**	**01.08.16 23:13**

if precipitation controls have always and everywhere in the study region the same impact or

Seite 4: [19] Gelöscht	**Julia Curio**	**01.08.16 23:13**

2.2. Methods

For the analyses in this study we selected the years 2001-2013 as study period and use daily HAR data. The data set is then stratified, because we are only interested in precipitation days, this is done month-wise. For example, all July analysis depend on the data basis of each July day during 2001-2013, these are 31*13 days, total 403 days. Therefor all analyses are conducted for precipitation days only. Precipitation days for a grid point are defined as days with a mean daily precipitation rate of 0.1 mm. This value

Seite 5: [20] Gelöscht	**Julia Curio**	**01.08.16 23:13**

, with a level of significance of 0.05, are plotted. Following this, a principal component analysis (PCA) was performed for the correlations between controls and precipitation to detect the dominant patterns.

Due to the use of correlations we avoid

Seite 5: [21] Gelöscht	**Julia Curio**	**01.08.16 23:13**

(green). This class represents a transition zone where the monsoon can have influence but is not dominant.

Seite 5: [22] Formatiert	**Julia Curio**	**01.08.16 23:13**

Abstand Vor: 0 Pt., Keine Absatzkontrolle, Leerraum zwischen asiatischem und westlichem Text nicht anpassen, Leerraum zwischen asiatischem Text und Zahlen nicht anpassen

Seite 6: [23] Gelöscht	**Julia Curio**	**01.08.16 23:13**

We only show the months with the most prominent features. Figures with the correlation of each dynamic control with precipitation for all months are provided in the supplemental material for completeness.

Seite 8: [24] Formatiert	**Julia Curio**	**01.08.16 23:13**

Schriftfarbe: Text 1

Seite 8: [24] Formatiert	**Julia Curio**	**01.08.16 23:13**

Schriftfarbe: Text 1

Seite 8: [25] Formatiert Julia Curio 01.08.16 23:13

Schriftfarbe: Text 1

Seite 8: [25] Formatiert Julia Curio 01.08.16 23:13

Schriftfarbe: Text 1

Seite 8: [26] Gelöscht Julia Curio 01.08.16 23:13

provides

Seite 8: [26] Gelöscht Julia Curio 01.08.16 23:13

provides

Seite 8: [26] Gelöscht Julia Curio 01.08.16 23:13

provides

Seite 8: [26] Gelöscht Julia Curio 01.08.16 23:13

provides

Seite 8: [26] Gelöscht Julia Curio 01.08.16 23:13

provides

Seite 8: [26] Gelöscht Julia Curio 01.08.16 23:13

provides

Seite 8: [26] Gelöscht Julia Curio 01.08.16 23:13

provides

Seite 8: [26] Gelöscht Julia Curio 01.08.16 23:13

provides

Seite 8: [26] Gelöscht Julia Curio 01.08.16 23:13

provides

Seite 8: [26] Gelöscht Julia Curio 01.08.16 23:13

provides

Seite 8: [26] Gelöscht **Julia Curio** **01.08.16 23:13**

provides

Seite 8: [27] Gelöscht **Julia Curio** **01.08.16 23:13**

,

Seite 8: [27] Gelöscht **Julia Curio** **01.08.16 23:13**

,

Seite 8: [27] Gelöscht **Julia Curio** **01.08.16 23:13**

,

Seite 8: [27] Gelöscht **Julia Curio** **01.08.16 23:13**

,

Seite 8: [27] Gelöscht **Julia Curio** **01.08.16 23:13**

,

Seite 8: [28] Gelöscht **Julia Curio** **01.08.16 23:13**

now we have

Seite 8: [28] Gelöscht **Julia Curio** **01.08.16 23:13**

now we have

Seite 8: [28] Gelöscht **Julia Curio** **01.08.16 23:13**

now we have

Seite 9: [29] Gelöscht **Julia Curio** **01.08.16 23:13**

3.2.4 Planetary boundary layer height (PBLH)

In Winter the correlation between PBLH and precipitation (Fig. 8) are mainly positive, especially in the PKwH Himalaya region, forming a coherent pattern, and along the northern and southern border of the TP, with some interruptions, and in the eastern TP around the Brahmaputra Channel. PBLH is a precipitation control which is itself controlled by horizontal wind speed, among others. The positive correlations in winter in the Pamir/Karakoram region can be explained by higher horizontal wind speeds and thereby more moisture advection leading to more precipitation, like described earlier. Higher horizontal wind speeds lead to higher entrainment rates at the top of the PBL whereby the depth of the PBL increases.

During the year this picture changes and negative correlations become dominant. The negative correlations occur in regions and seasons dominated by convection and consequently convective precipitation. Higher PBLH are caused by higher horizontal wind speeds which have a negative effect on precipitation by cutting off deep convection, as previously pointed out in this study. In May we see positive correlations left only in the centre of the Pamir/Karakoram region and in the eastern TP, while in summer just small and scattered areas with positive correlations occur. Most of these areas on the central TP match with the large lakes, e.g. Nam Co, Serling Co, and Tangra Yumco.

To understand these contrary correlations, compared with the direct surroundings of the lakes, we have to look at the PBLH itself. Figure 9 shows the averaged daily mean and daily maximum PBLH for May as an example. The lowest PBLHs (mean and maximum) in the domain are found at the high mountain ranges bordering the TP, because of the high altitudes and low temperatures, and above the large lakes on the central TP. Reason for this seems to be the fact that during daytime when the air temperature above land is higher than above the lakes, the air above the land starts to ascend and there is strong convective activity which is amplified at the slopes of the surrounding mountain ranges (due to higher solar insulation). Recirculation of the ascended air leads to subsidence of air above the lakes which lowers the PBLH and supresses precipitation. Suppression of precipitation by subsidence was already described in Curio et al. (2015) for larger regions like the Qaidam Basin and the north-western parts of India and Pakistan.

The positive correlations above the lakes, mean that higher PBLH leads to more precipitation in this area. These higher PBLH occur when the wind speeds are higher, which leads to more entrainment, which causes a deepening of the PBL above the lakes. This effect slightly equalizes the PBLHs above the lakes and the surrounding land and the differences become smaller. Due to the increase of the PBLH, the prevailing subsidence above the lakes weakens and precipitation development becomes possible.

Seite 11: [30] Gelöscht **Julia Curio** **01.08.16 23:13**

Seite 15: [31] Gelöscht **Julia Curio** **01.08.16 23:13**

and

Seite 15: [31] Gelöscht **Julia Curio** **01.08.16 23:13**

and

Seite 15: [32] Formatiert **Julia Curio** **01.08.16 23:13**

Schriftart:Kursiv

Seite 15: [32] Formatiert **Julia Curio** **01.08.16 23:13**

Schriftart:Kursiv

Seite 15: [33] Formatiert **Julia Curio** **01.08.16 23:13**

Einzug: Links: 0 cm, Hängend: 0,85 cm

Seite 15: [34] Formatiert **Julia Curio** **01.08.16 23:13**

Schriftart:Kursiv

Seite 15: [34] Formatiert **Julia Curio** **01.08.16 23:13**

Schriftart:Kursiv

Seite 15: [35] Formatiert **Julia Curio** **01.08.16 23:13**

Einzug: Links: 0 cm, Hängend: 0,75 cm

Seite 15: [36] Formatiert **Julia Curio** **01.08.16 23:13**

Englisch (Vereinigtes Königreich)

Seite 15: [37] Formatiert **Julia Curio** **01.08.16 23:13**

Englisch (Vereinigtes Königreich)

Seite 15: [38] Gelöscht **Julia Curio** **01.08.16 23:13**

a. M., D'Andrea, F., and Ek, M.: Surface and Atmospheric

Seite 15: [39] Formatiert **Julia Curio** **01.08.16 23:13**

Englisch (Vereinigtes Königreich)

Seite 15: [40] Formatiert **Julia Curio** **01.08.16 23:13**

Englisch (Vereinigtes Königreich)

Seite 15: [41] Formatiert **Julia Curio** **01.08.16 23:13**

Englisch (Vereinigtes Königreich)

Seite 15: [41] Formatiert **Julia Curio** **01.08.16 23:13**

Englisch (Vereinigtes Königreich)

Seite 15: [41] Formatiert **Julia Curio** **01.08.16 23:13**

Englisch (Vereinigtes Königreich)

Seite 15: [42] Formatiert **Julia Curio** **01.08.16 23:13**

Englisch (Vereinigtes Königreich)

Seite 15: [43] Formatiert **Julia Curio** **01.08.16 23:13**

Schriftart:Kursiv

Seite 15: [44] Gelöscht **Julia Curio** **01.08.16 23:13**

. doi: http://journals.ametsoc.org/doi/abs/10.1175/1520-0469(1975)032<

Seite 15: [44] Gelöscht **Julia Curio** **01.08.16 23:13**

. doi: http://journals.ametsoc.org/doi/abs/10.1175/1520-0469(1975)032<

Seite 15: [45] Formatiert **Julia Curio** **01.08.16 23:13**

Schriftart:Kursiv

Seite 15: [45] Formatiert **Julia Curio** **01.08.16 23:13**

Schriftart:Kursiv

Seite 15: [46] Gelöscht **Julia Curio** **01.08.16 23:13**

http://dx.doi.org/

Seite 15: [46] Gelöscht **Julia Curio** **01.08.16 23:13**

http://dx.doi.org/

Seite 15: [47] Gelöscht **Julia Curio** **01.08.16 23:13**

and

Seite 15: [47] Gelöscht **Julia Curio** **01.08.16 23:13**

and

Seite 15: [48] Formatiert **Julia Curio** **01.08.16 23:13**

Schriftart:Kursiv

Seite 15: [48] Formatiert **Julia Curio** **01.08.16 23:13**

Schriftart:Kursiv

Seite 15: [49] Gelöscht **Julia Curio** **01.08.16 23:13**

Janjic, Z. I.: Nonsingular Implementation of the Mellor-Yamada Level 2.5 Scheme in the NCEP Meso model. National Centers for Environmental Prediction Office Note, #437, 61, 2002.

Seite 15: [50] Gelöscht **Julia Curio** **01.08.16 23:13**

and

Seite 15: [50] Gelöscht **Julia Curio** **01.08.16 23:13**

and

Seite 15: [51] Formatiert **Julia Curio** **01.08.16 23:13**

Schriftart:Kursiv

Seite 15: [51] Formatiert **Julia Curio** **01.08.16 23:13**

Schriftart:Kursiv

Seite 15: [52] Formatiert **Julia Curio** **01.08.16 23:13**

Einzug: Links: 0 cm, Hängend: 0,85 cm

Seite 15: [53] Gelöscht **Julia Curio** **01.08.16 23:13**

and

Seite 15: [53] Gelöscht **Julia Curio** **01.08.16 23:13**

and

Seite 15: [54] Formatiert **Julia Curio** **01.08.16 23:13**

Schriftart:Kursiv

Seite 15: [54] Formatiert **Julia Curio** **01.08.16 23:13**

Schriftart:Kursiv

Seite 15: [55] Formatiert **Julia Curio** **01.08.16 23:13**

Einzug: Links: 0 cm, Hängend: 0,75 cm

Seite 15: [56] Gelöscht **Julia Curio** **01.08.16 23:13**

and

Seite 15: [56] Gelöscht **Julia Curio** **01.08.16 23:13**

and

Seite 15: [57] Formatiert **Julia Curio** **01.08.16 23:13**

Schriftart:Kursiv

Seite 15: [57] Formatiert **Julia Curio** **01.08.16 23:13**

Schriftart:Kursiv

Seite 15: [58] Gelöscht **Julia Curio** **01.08.16 23:13**

and

Seite 15: [58] Gelöscht **Julia Curio** **01.08.16 23:13**

and

**Seite 15: [59] Formatiert	Julia Curio	01.08.16 23:13**

Schriftart:Kursiv

**Seite 15: [60] Formatiert	Julia Curio	01.08.16 23:13**

Schriftart:Kursiv

**Seite 15: [60] Formatiert	Julia Curio	01.08.16 23:13**

Schriftart:Kursiv

**Seite 15: [61] Gelöscht	Julia Curio	01.08.16 23:13**

Ma, Y., Wang, Y., Wu, R., Hu, Z., Yang, K., Li, M., Ma, W., Zhong, L., Sun, F., Chen, X., Zhu, Z., Wang, S., and Ishikawa, H.: Recent advances on the study of atmosphere-land interaction observations on the Tibetan Plateau. Hydrology and Earth System Sciences, 13(7), 1103–1111. doi:10.5194/hess-13-1103-2009, 2009.

**Seite 15: [61] Gelöscht	Julia Curio	01.08.16 23:13**

Ma, Y., Wang, Y., Wu, R., Hu, Z., Yang, K., Li, M., Ma, W., Zhong, L., Sun, F., Chen, X., Zhu, Z., Wang, S., and Ishikawa, H.: Recent advances on the study of atmosphere-land interaction observations on the Tibetan Plateau. Hydrology and Earth System Sciences, 13(7), 1103–1111. doi:10.5194/hess-13-1103-2009, 2009.

**Seite 15: [61] Gelöscht	Julia Curio	01.08.16 23:13**

Ma, Y., Wang, Y., Wu, R., Hu, Z., Yang, K., Li, M., Ma, W., Zhong, L., Sun, F., Chen, X., Zhu, Z., Wang, S., and Ishikawa, H.: Recent advances on the study of atmosphere-land interaction observations on the Tibetan Plateau. Hydrology and Earth System Sciences, 13(7), 1103–1111. doi:10.5194/hess-13-1103-2009, 2009.

**Seite 15: [62] Formatiert	Julia Curio	01.08.16 23:13**

Schriftart:Kursiv

**Seite 15: [62] Formatiert	Julia Curio	01.08.16 23:13**

Schriftart:Kursiv

**Seite 16: [63] Gelöscht	Julia Curio	01.08.16 23:13**

Medeiros, B., Hall, A., & Stevens, B.: What controls the mean depth of the PBL? Journal of Climate, 18(16), 3157–3172. doi:10.1175/JCLI3417.1, 2005.

**Seite 16: [63] Gelöscht	Julia Curio	01.08.16 23:13**

Medeiros, B., Hall, A., & Stevens, B.: What controls the mean depth of the PBL? Journal of Climate, 18(16), 3157–3172. doi:10.1175/JCLI3417.1, 2005.

**Seite 16: [63] Gelöscht	Julia Curio	01.08.16 23:13**

Medeiros, B., Hall, A., & Stevens, B.: What controls the mean depth of the PBL? Journal of Climate, 18(16), 3157–3172. doi:10.1175/JCLI3417.1, 2005.

**Seite 16: [64] Gelöscht	Julia Curio	01.08.16 23:13**

, 1439–1455

**Seite 16: [64] Gelöscht	Julia Curio	01.08.16 23:13**

, 1439–1455

**Seite 16: [65] Gelöscht	Julia Curio	01.08.16 23:13**

and

Seite 16: [65] Gelöscht **Julia Curio** **01.08.16 23:13**

and

Seite 16: [66] Gelöscht **Julia Curio** **01.08.16 23:13**

., Reudenbach, C., Thies, B., and Bendix, J.:

Seite 16: [66] Gelöscht **Julia Curio** **01.08.16 23:13**

., Reudenbach, C., Thies, B., and Bendix, J.:

Seite 16: [67] Formatiert **Julia Curio** **01.08.16 23:13**

Schriftart:Kursiv

Seite 16: [67] Formatiert **Julia Curio** **01.08.16 23:13**

Schriftart:Kursiv

Seite 16: [68] Gelöscht **Julia Curio** **01.08.16 23:13**

and

Seite 16: [68] Gelöscht **Julia Curio** **01.08.16 23:13**

and

Seite 16: [68] Gelöscht **Julia Curio** **01.08.16 23:13**

and

Seite 16: [68] Gelöscht **Julia Curio** **01.08.16 23:13**

and

Seite 16: [68] Gelöscht **Julia Curio** **01.08.16 23:13**

and

Seite 16: [69] Gelöscht **Julia Curio** **01.08.16 23:13**

and

Seite 16: [69] Gelöscht **Julia Curio** **01.08.16 23:13**

and

Seite 16: [70] Formatiert **Julia Curio** **01.08.16 23:13**

Schriftart:Kursiv

Seite 16: [70] Formatiert **Julia Curio** **01.08.16 23:13**

Schriftart:Kursiv

Seite 16: [71] Gelöscht **Julia Curio** **01.08.16 23:13**

and

Seite 16: [71] Gelöscht **Julia Curio** **01.08.16 23:13**

and

Seite 16: [72] Formatiert **Julia Curio** **01.08.16 23:13**

Schriftart:Kursiv

Seite 16: [72] Formatiert **Julia Curio** **01.08.16 23:13**

Schriftart:Kursiv

Seite 16: [73] Gelöscht **Julia Curio** **01.08.16 23:13**

and

Seite 16: [73] Gelöscht **Julia Curio** **01.08.16 23:13**

and

Seite 16: [74] Gelöscht **Julia Curio** **01.08.16 23:13**

and

Seite 16: [74] Gelöscht **Julia Curio** **01.08.16 23:13**

and

Seite 16: [75] Formatiert **Julia Curio** **01.08.16 23:13**

Schriftart:Kursiv

Seite 16: [75] Formatiert **Julia Curio** **01.08.16 23:13**

Schriftart:Kursiv

Seite 16: [76] Gelöscht **Julia Curio** **01.08.16 23:13**

Vachon, R., and

Seite 16: [76] Gelöscht **Julia Curio** **01.08.16 23:13**

Vachon, R., and

Seite 16: [77] Formatiert **Julia Curio** **01.08.16 23:13**

Schriftart:Kursiv

Seite 16: [77] Formatiert **Julia Curio** **01.08.16 23:13**

Schriftart:Kursiv

Seite 16: [78] Gelöscht **Julia Curio** **01.08.16 23:13**

,

Seite 16: [78] Gelöscht **Julia Curio** **01.08.16 23:13**

,

Seite 16: [79] Formatiert **Julia Curio** **01.08.16 23:13**

Schriftart:Kursiv

Seite 16: [79] Formatiert **Julia Curio** **01.08.16 23:13**

Schriftart:Kursiv

Seite 16: [80] Gelöscht **Julia Curio** **01.08.16 23:13**

N., Shukla, J., Tomas, R. A., Yanai, M., and Yasunari, T.:

Seite 16: [80] Gelöscht **Julia Curio** **01.08.16 23:13**

N., Shukla, J., Tomas, R. A., Yanai, M., and Yasunari, T.:

Seite 16: [81] Gelöscht **Julia Curio** **01.08.16 23:13**

,

Seite 16: [81] Gelöscht **Julia Curio** **01.08.16 23:13**

,

Seite 16: [82] Gelöscht **Julia Curio** **01.08.16 23:13**

Wilks, D. S.: Statistical Methods in the Atmospheric Sciences: An Introduction. Academic Press, 1995.

Seite 16: [82] Gelöscht Julia Curio 01.08.16 23:13

Wilks, D. S.: Statistical Methods in the Atmospheric Sciences: An Introduction. Academic Press, 1995.

Seite 16: [82] Gelöscht Julia Curio 01.08.16 23:13

Wilks, D. S.: Statistical Methods in the Atmospheric Sciences: An Introduction. Academic Press, 1995.

Seite 16: [82] Gelöscht Julia Curio 01.08.16 23:13

Wilks, D. S.: Statistical Methods in the Atmospheric Sciences: An Introduction. Academic Press, 1995.

Seite 16: [82] Gelöscht Julia Curio 01.08.16 23:13

Wilks, D. S.: Statistical Methods in the Atmospheric Sciences: An Introduction. Academic Press, 1995.

Seite 16: [83] Gelöscht Julia Curio 01.08.16 23:13

Yang, K., Koike, T., Fujii, H., Tamura, T., Xu, X., Bian, L., and Zhou, M.: The Daytime Evolution of the Atmospheric Boundary Layer and Convection over the Tibetan Plateau: Observations and Simulations. Journal of the Meteorological Society of Japan, *82*(6), 1777–1792. doi:10.2151/jmsj.82.1777, 2004.

Seite 16: [83] Gelöscht Julia Curio 01.08.16 23:13

Yang, K., Koike, T., Fujii, H., Tamura, T., Xu, X., Bian, L., and Zhou, M.: The Daytime Evolution of the Atmospheric Boundary Layer and Convection over the Tibetan Plateau: Observations and Simulations. Journal of the Meteorological Society of Japan, *82*(6), 1777–1792. doi:10.2151/jmsj.82.1777, 2004.

Seite 17: [84] Gelöscht Julia Curio 01.08.16 23:13

Seite 20: [85] Gelöscht Julia Curio 01.08.16 23:13

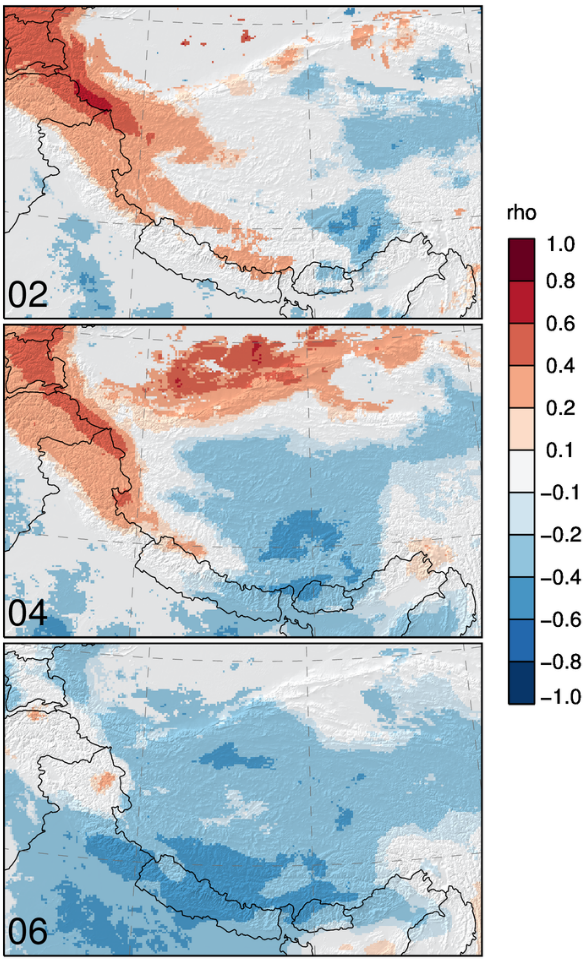


Fig.

Seite 20: [86] Gelöscht **Julia Curio** **01.08.16 23:13**

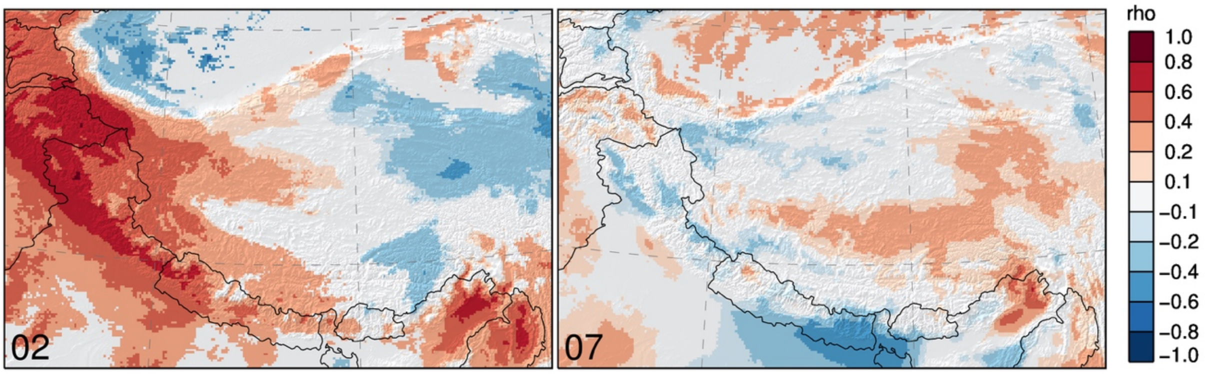


Fig.

Seite 21: [87] Gelöscht **Julia Curio** **01.08.16 23:13**

February (02) and July (07). Positive correlations are denoted in red, while negative correlations are denoted in blue.

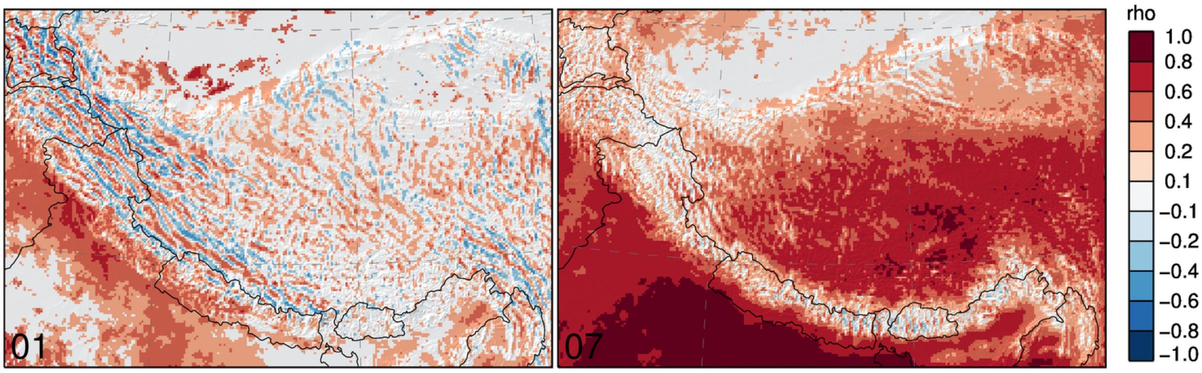
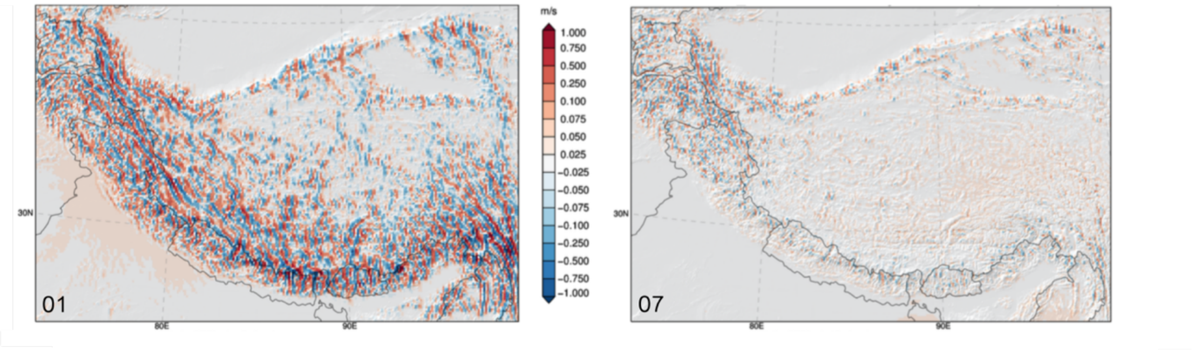


Fig. 5: Coefficient of correlation (rho) between vertical wind speed at 300 hPa (W300) and precipitation for January (01) and July (07).

Seite 22: [88] Gelöscht **Julia Curio** **01.08.16 23:13**



Seite 22: [89] Auf Seite 24 verschoben (Verschiebung Nr. 6) **Julia Curio**
01.08.16 23:13

Fig. 6: Mean vertical wind speed at 300 hPa for January (01) and July (07).

Seite 23: [90] Gelöscht **Julia Curio** **01.08.16 23:13**

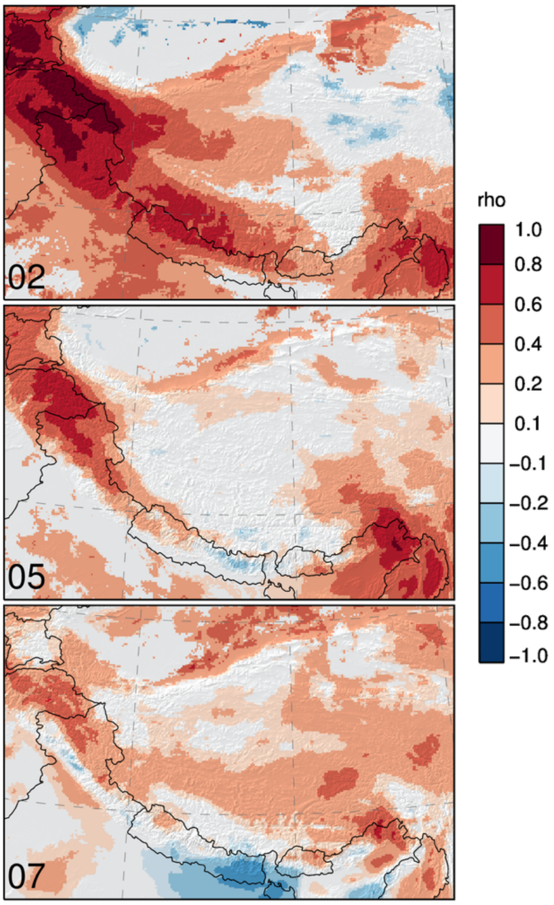


Fig. 7:

Seite 25: [91] Gelöscht **Julia Curio** **01.08.16 23:13**

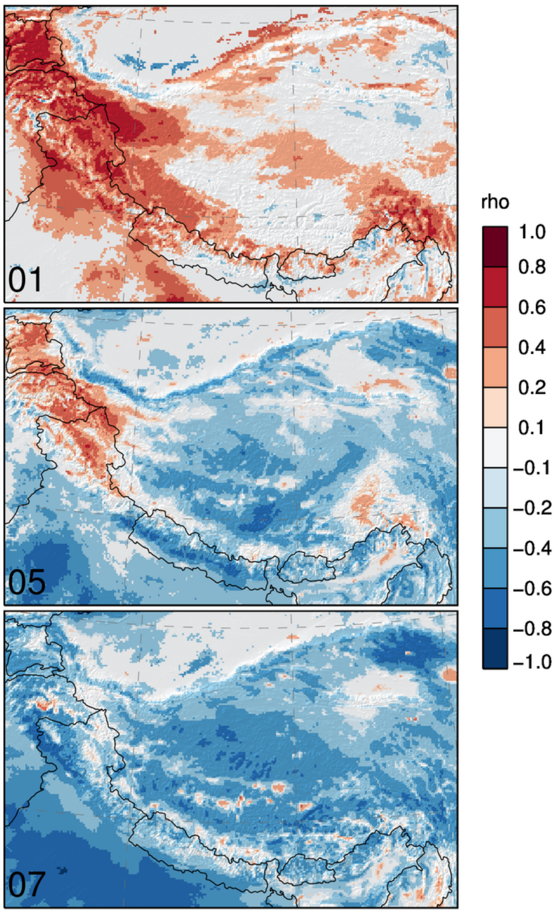


Fig. 8:

Seite 26: [92] Gelöscht **Julia Curio** **01.08.16 23:13**

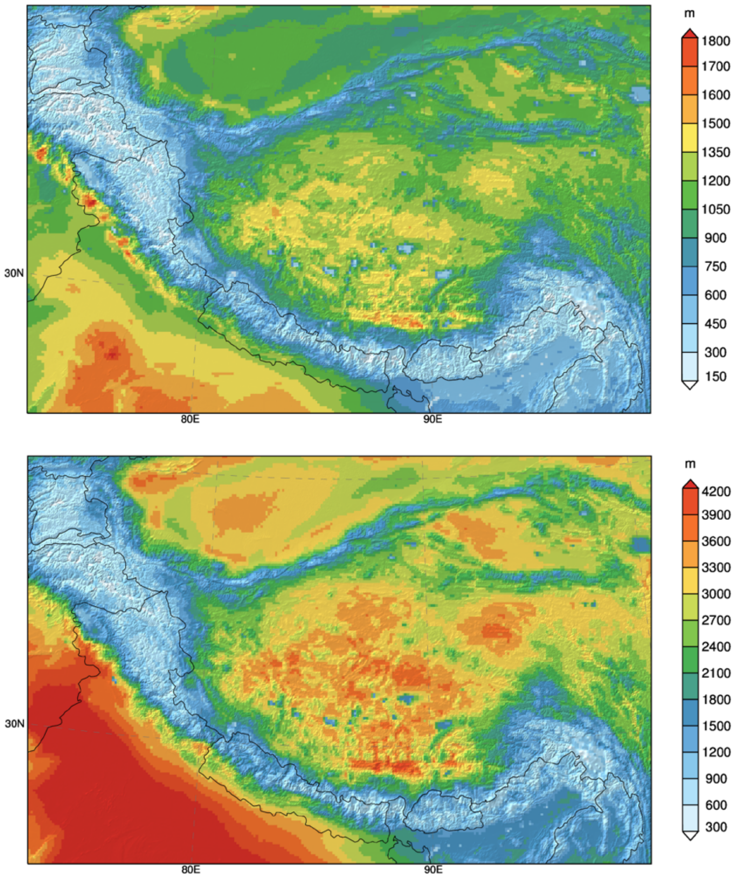
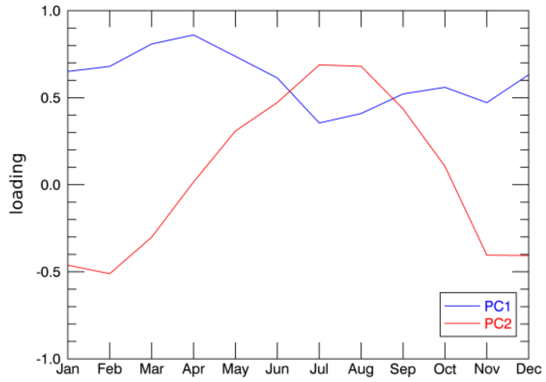
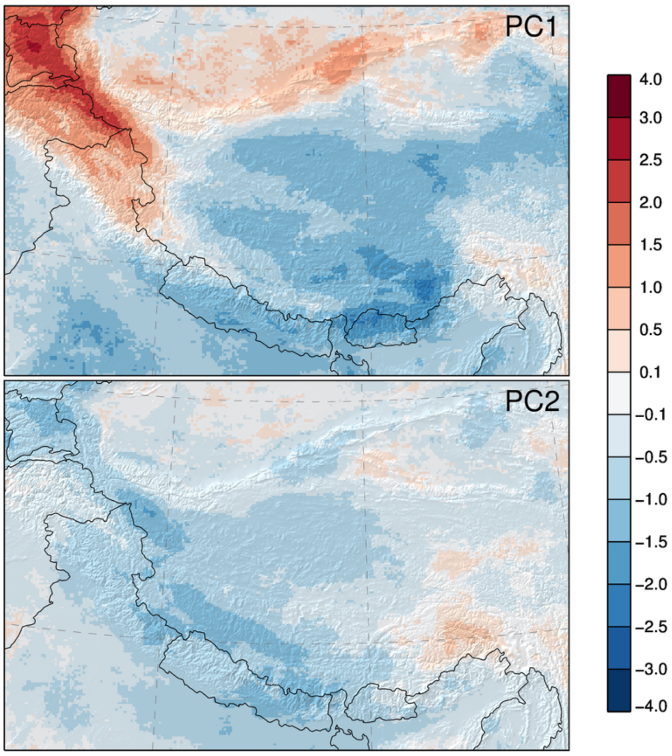


Fig. 9: Planetary boundary layer height (m) daily mean (top) and mean daily maximum (bottom) in May (2001-2013).



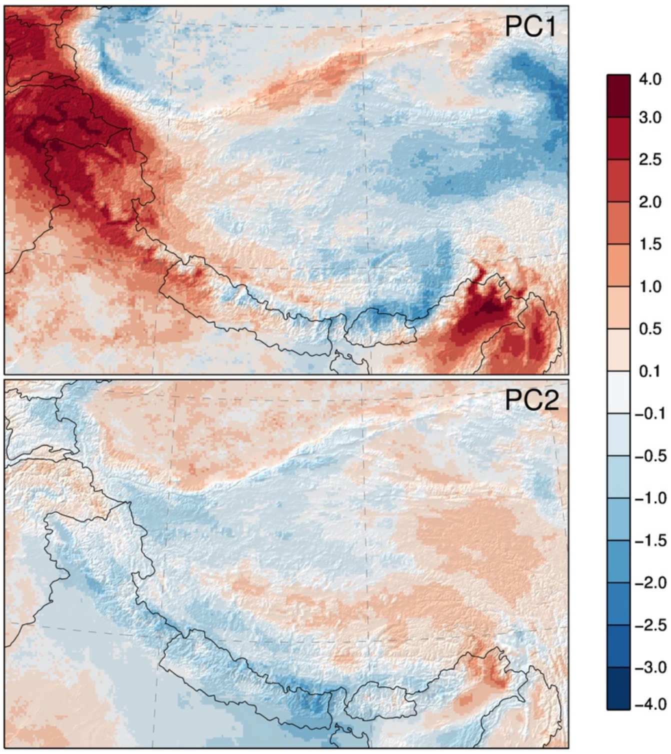
(a)

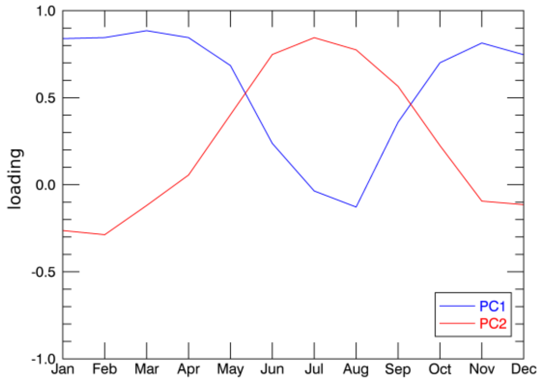


(b)

Seite 27: [93] Gelöscht **Julia Curio** **01.08.16 23:13**

(a)

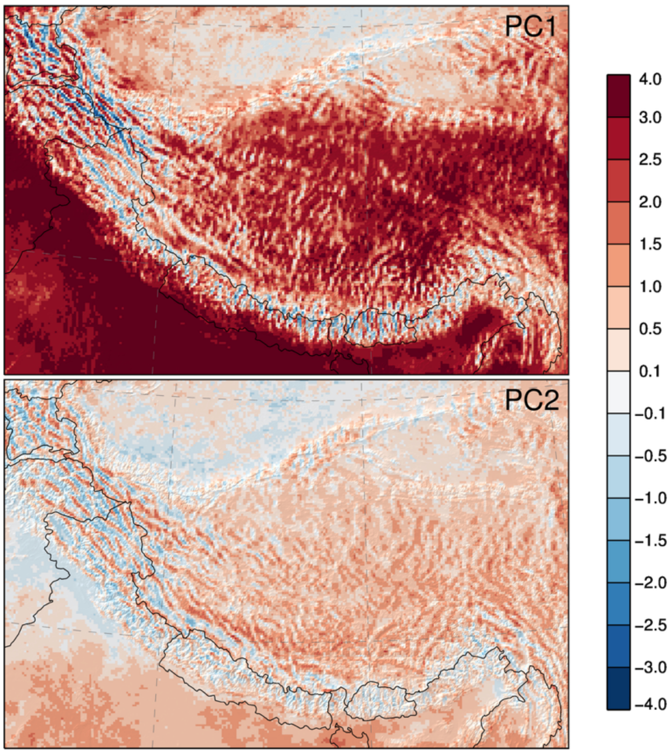


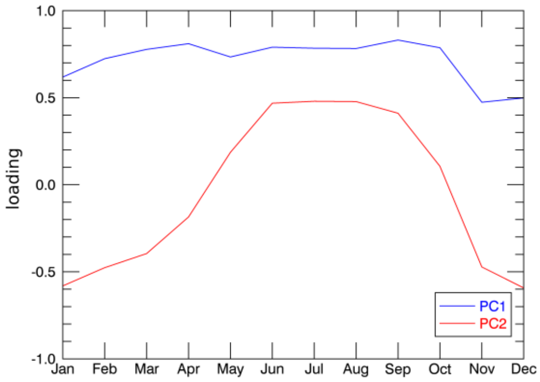


(b)

Seite 28: [94] Gelöscht **Julia Curio** **01.08.16 23:13**

(a)

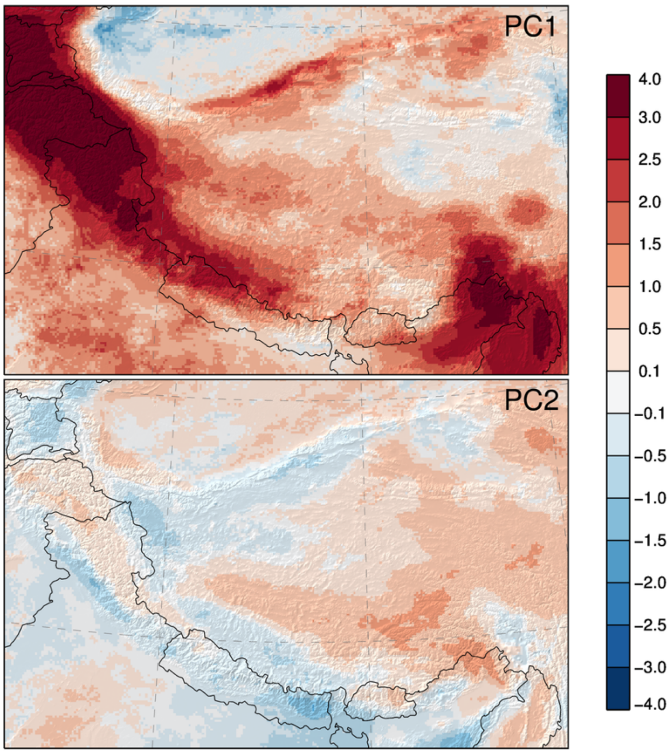

PC1
PC2
4.0
3.0
2.5
2.0
1.5
1.0
0.5
0.1
−0.1
−0.5
−1.0
−1.5
−2.0
−2.5
−3.0
−4.0

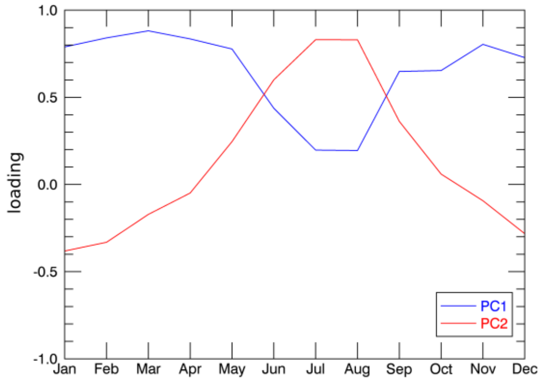


(b)

Seite 29: [95] Gelöscht **Julia Curio** **01.08.16 23:13**

(a)

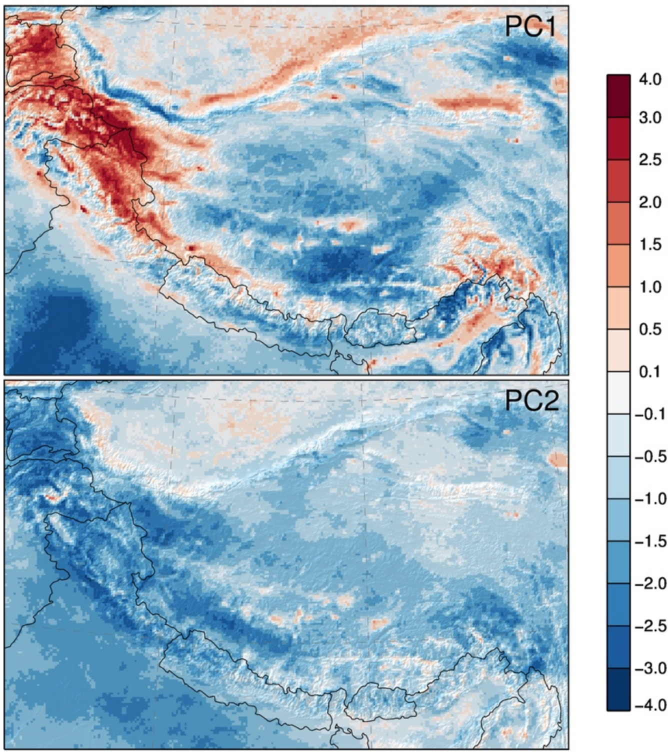


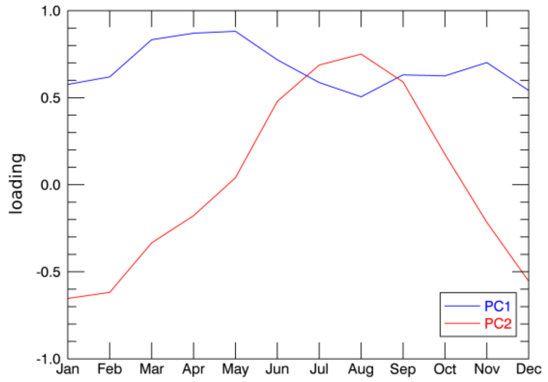


(b)

Seite 30: [96] Gelöscht **Julia Curio** **01.08.16 23:13**

(a)





(b)

Figure 14. Scores of first two principal components PC1 and PC2 for the correlation between planetary boundary layer height (PBLH) and precipitation **(a)** (positive values are denoted in red, while negative values are denoted in blue) and the monthly loadings **(b)** for both PCs.