Replies to Interactive comment on "Influence of regional precipitation patterns on stable isotopes in ice cores from the central Himalayas" by **H. Pang et al.**

Note: The reviewer's comments are in black, and our replies in blue.

Anonymous Referee #2

General comments

Influence of regional precipitation patterns on stable isotopes by H. Pang et al raises a very interesting issue (i.e., different interpretation of ice core $\delta^{18}O$ retrieved from nearby glaciers on the Himalayas). The study tries to address the issue, and come up with possible mechanisms leading to those different interpretations. Tremendous efforts have been devoted to the atmospheric circulations patterns and atmospheric physics likely functioning in the process. The authors should be commended for their scientific and innovative spirits in delving deep to extract possible factors at play in ice core stable isotopes at different locations on the Himalayas.

However, for ice core sites so close to each other, the authors may need to look into their unique geographical locations and differences before introducing climatological differences. Otherwise, both sites are expected to experience the same large-scale (e.g. monsoon and westerlies) and/or meso-scale circulation systems. Besides, the much lower elevation of the ER than Dasuopu may subject the former to wind scouring and re-deposition of snow. Thus the core information in ER may not be directly affected by large-scale atmospheric circulation, but rather by local and secondary effects.

We agree with you about local different topographical conditions between Dasuopu (DSP) and East Rongbuk (ER) glaciers and their potential contributor to the different interpretations of the DSP and ER $\delta^{18}O$ records. Following your suggestion, we included an introduction about local topographic features of DSP and ER glaciers in Section 2.2. Three-dimensional topographic maps of the DSP and ER glaciers were plotted using the high-resolution ASTER DEM data, as shown in Fig. 1b. The DSP drilling site is located on the Mt. Shishapangma ridge, which extends in a northwest-southeast direction, facing relatively low terrains in the south and in the west (Fig. 1b). This provides a broad space for the western disturbances invading and developing. Moreover, the northwest-southeast ridge of Mt. Shishapangma is diagonal to the westerly flow, which is favorable for interacting with the western disturbances, probably leading to significant wintertime precipitation at the DSP drilling site. On the other hand, the ER core was retrieved from the East Rongbuk Col on the northeast ridge of Mt. Qomolangma (Everest). The very high west and southeast ridges of Mt. Qomolangma (Everest) in the south (Fig. 1b) may constrain the western disturbances in the southern slope of Mt. Qomolangma (Everest) ridges, resulting in less wintertime precipitation at the ER drilling site. Therefore, the ER drilling site is equivalently situated in the leeward slope (rain shadow region) of the western disturbances, in contrast to the Dasuopu drilling site that is heavily influenced by the western disturbances.

We agree about the potential influence of the in-situ conditions at the ER core site, such as wind scouring or sublimation of snow. Low accumulation rate with small variation amplitude at the ER drilling site before the late 1930s is primarily a result of the weakening of the Indian monsoon circulation. Wind scouring or sublimation of snow may also be involved, but is hard to be quantified.

The paper in its current form is not easy to follow, due mainly to the diverse interpretation and mechanisms introduced to understand the issue. There is also a lack of comparison with previous studies regarding the proposed interplay between the proposed interplay between the westerlies and Indian monsoon. The authors proposed reverse evolution of the westerlies and Indian summer monsoon as the mechanisms for different interpretation of ice core $\delta^{18}O$ for Dasuopu and ER, and suggest a weakening westerlies and intensifying summer monsoon due to global warming. Is such an indication consistent with studies as An et al. 2012 and Yao et al., 2012? A brief graph, or sentence is needed here to summarize the comparison and propose some causes for the differences, if any.

An et al (2012) reported the anti-phase relationship of the Westerlies and the Asian summer monsoon for both glacial-interglacial and glacial millennial timescales using high-resolution sediment records from Lake Qinghai on the northeastern Tibetan Plateau. Yao et al (2012) reported an increasing precipitation trend in the eastern Pamir and a decreasing precipitation trend in the Himalayas during the past 30 years. In our paper, we identified a reverse trend between the DSP and ER accumulation rates during the past 200 years. All the observations are indicative of interplay between the two large-scale atmospheric systems, but for different timescales.

In general, I opt for major revision for this paper. Before looking at the large-scenario for causes of the ice core $\delta^{18}O$ differences at both glaciers, the authors are suggested to first study the local geomorphology and potential local effect. I think in situ observation in nearby areas may be more convincing evidences for the verification of ice core $\delta^{18}O$ climate significance. Thus field observation of precipitation patterns on different slopes may supplement the understanding, and continuous sampling of precipitation in the region for stable isotopes analysis is also conducive to understanding the problem.

To further verify precipitation seasonality along the Himalayas inferred from the climatological observations from the four Himalayan weather stations, spatial distribution of non-monsoon season (October to May) precipitation ratio to annual precipitation over the study area is calculated using a high resolution reanalysis data (Fig. 4). It is clear that the non-monsoon season precipitation ratio over the western high Himalayas (40-80%) is higher than that over the southern and northern slopes of Himalayas (<20%), suggesting that local capture of the westerlies moisture by mountain topography (western high Himalayas) is evident. Furthermore, the non-monsoon precipitation ratio seems to gradually decrease from the western to central Himalayas due to moisture wastage by sequential condensation of the westerlies moisture during its being transported eastward. In the central Himalayas, however, the non-monsoon precipitation ratio is highly changeable in the place that the Dasuopu and the ER ice cores are located. For instance, the non-monsoon precipitation ratio at the Nyalam weather station (nearby Dasuopu core) can reach 53%, while the ratio at the Dingri weather station (nearby ER core) is less than 10%. The highly variable non-monsoon precipitation ratio over the central Himalayas, in other words, the remarkable discrepancy of the non-monsoon precipitation ratio between Dasuopu and ER, is likely due to their local topographic features as shown in Fig. 1b.

Specific comments

3. Data

Introduction of the ice cores should follow the times series, i.e., Dasuopu first, and followed by ER. It should also follow the relevance of those data to understanding the issue, i.e., how the appearance of those data is arranged throughout the paper. Thus ice core information should be followed by regional precipitation data, and then by instrumental rainfall data over India, and finally by the reanalysis data.

Changes have been made accordingly in the revision.

Besides, elevation information of the ice coring sites should be mentioned, as it directly influences the accumulation and climate significance in ice core $\delta^{18}O$.

Previous studies show that most annual precipitation at low altitudes of the central Himalayas falls during the ISM season (Shrestha 2000; Lang and Barros, 2004), while Lang and Barros (2004) found that high elevations (>3000 m a.s.l.) in the central Himalayas can receive up to 40% of their annual precipitation during winter. The result seems to imply that wintertime precipitation associated with the western disturbances in the central Himalayas increases with rising elevation. The local advantageous topographic conditions would make considerable wintertime precipitation falling at the DSP core site. On the other hand, according to investigation on altitudinal distribution of the Indian summer monsoon rainfall in the central Himalayas, Dhar and Rakhecha (1981) indicated that the zones of maximum rainfall occur near the foothills at an elevation of 2000 to 2400 m a.s.l.. Beyond the elevation, rainfall decreases continuously as elevation increases until the great Himalayan range is reached. The result suggests that the ISM precipitation above the elevation of 2000 to 2400 m a.s.l. decreases significantly with rising elevation in the southern slope of Himalayas.

With elevation rising in the central Himalayas, the potential increase in wintertime precipitation associated with the westerlies and the decrease in summertime precipitation related to the ISM probably lead to larger proportion of wintertime precipitation than the summertime precipitation ratio at the DSP core site. However, the very high Mt. Qomolangma (Everest) ridges may effectively impede the western disturbances, which results in little wintertime precipitation at the ER core site. On the other hand, the 700 m elevation difference between the two ice core sites may cause little difference in summer monsoon precipitation between the two sites because the convective system of precipitation of the ISM can reach a high elevation.

The motivation to compare with rainfall in India is missing. Maybe the authors take the rainfall in India as Indian monsoon index, and that in different part of India as resulted from contributions of different moisture trajectories? Such a rationale is needed for the introduction of the Indian precipitation and its spatial pattern.

Because the four Indian homogenous rainfall regions (i.e., NMI: North Mountainous India; NWI: North West India; NCI: North Central India; NEI: North East India) are directly adjacent to the Himalayas, the instrumental summer monsoon rainfall series in these monsoon-impacted regions are used for comparison with the Himalayan ice records,

4. Regional precip….

The presentation of long-term monthly distribution of precipitation at the four stations along the Himalayas is informative. The authors should clearly define "western" and "eastern" Himalayas as some stations are pretty close to each other, e.g., Dingri and Nylam.

In the revision, we define "western Himalayas" as the region where seasonal distribution of precipitation is bimodal and "eastern Himalayas" as the region where seasonal distribution of precipitation is unimodal. Based on this criterion, we demarcate the boundary nearby Mt. Qomolangma (Everest) as shown in Fig. 4. So to the west of Mt. Qomolangma (Everest) is defined as "western Himalayas" and to the east of Mt. Qomolangma (Everest) as "eastern Himalayas".

The study would also benefit from correlation analysis of precipitation $\delta^{18}O$ with climatic parameters in modern precipitation at those stations, if available.

Correlation analysis of precipitation $\delta^{18}O$ with climatic parameters in the study area has been performed in previous studies. For instance, Zhang et al (2005) calculated the correlation coefficients between the annual $\delta^{18}O$ record from an 80.36 m ice core in the East Rongbuk Glacier and air temperature from 19 meteorological stations on the Qinghai-Tibetan Plateau which lie to the north of Himalayas and 17 stations on the Indian Subcontinent to the south of Himalayas (Table 1 of their paper). They found no obvious correlations exist between the annual $\delta^{18}O$ and temperature records, suggesting that the ER $\delta^{18}O$ record is not influenced by temperature, and that the $\delta^{18}O$ records of the East Rongbuk ice core should be a proxy of Indian summer monsoon intensity. In addition, the correlation between the mean annual δD of the ER core and precipitation nearby the ER core site has been analyzed by Kaspari et al (2007). They found the mean annual ER δD is inversely correlated with: annual precipitation rate at nearby Nyalam station; the June-September precipitation rate deriving from the NCEP/NCAR reanalysis over the Everest region (31ºN, 92ºE) from 1948-2001; and the June-September precipitation rate over the north central India (the closest region to Everest) from 1871-2001. This verifies that the amount effect plays an important role in the isotopic composition of Everest precipitation.

In addition, Tian et al (2005) analyzed the temporal variation of d-excess of individual precipitation from September 1999 to May 2001 at Nyalam, and found the d-excess values in winter-spring season are high, which is due to a substantial winter and spring precipitation associated with the westerlies.

As result, we don't perform the correlation analysis of precipitation $\delta^{18}O$ with climatic parameters in the revision. The correlation analysis mentioned above is cited in the revision.

Otherwise, the study clearly depicts the different regional precipitation patterns, with the western Himalayas characterized by bimodal whereas the eastern Himalayas characterized by uni-modal. Such precipitation spatial feature suggests possible difference in atmospheric circulation systems at play in the Himalayas, which offers an insight in the different mechanism driving precipitation $\delta^{18}O$ variation at those two drilling sites. However, the paper then turned to analyze the impacts of regional precipitation patterns in the Indian peninsular on ice core $\delta^{18}O$, followed by atmospheric circulation systems over the region, and detailed study of meteorological parameters including OLR, mid-upper troposphere summer mean temperature, and sensible heat flux. I find those analyses not very relevant and compelling, as I was at loss as to what those atmospheric analyses intend to prove.

We agree that some parts concerning to the spatial fluctuations of the Indian summer monsoon and their influence on the Himalayan ice core isotopic records are little relevant to the paper's goal, which is also pointed out by the other two reviewers. Thus, we decide to delete this content in the revision

5. Potential mechanisms…

In this section, the authors seem to have proposed possible mechanisms behind different $\delta^{18}O$ variations at those two ice coring sites, in terms of, respectively, geographical features, and synoptic scenarios.

Subtitle for section 5.1 is better renamed as "Unique geographical features associated with different precipitation seasonality along the Himalayas".

Yes the section has been renamed as "Unique geographical features associated with different precipitation seasonality along the Himalayas" in the revision.

In Section 5.2, the north-south seesaw is associated with the seasonal shift of the ITCZ, while the east-west seesaw is mainly related to a latest discovery by Wu et al (2012) about the importance of the Iran Plateau in triggering this feature. The IOD is also touched upon to understand the east-west seesaw pattern in precipitation over India. Those seesaw patterns and related synoptic scenarios and underlying mechanisms, however, seem to have been well documented in the atmospheric circle. In other words, the authors may need to shorten this part by highlighting some major concepts and mechanisms potentially functioning behind the different $\delta^{18}O$ features at those two ice coring sites.

The current description of those seesaw patterns in ISM precipitation is a bit verbose, and somewhat far-fetched from the scientific question addressed in the study.

Yes this part concerning the ISM seesaw patterns was deleted in the revision.

6. Discussion

The authors proposed one more possible factor in the different precipitation seasonality of East Rongbuk (ER) and Dasuopu ice coring sites, i.e., higher elevation of Dasuopu than ER, which offers an innovative insight. But the citation about high elevations (>3000 m a.s.l.) receive up to 40% of annual precipitation during winter may not be proper, as both ER and Dasuopu are higher than 3000 m a.s.l., therefore should yield little difference here.

Yes we have re-wrote this content.

Besides, the discussion of topographic condition as possible mechanism for the precipitation seasonality, therefore different ice core $\delta^{18}O$ signals at those two sites should go with the section 5. In fact, this section is better integrated with section 5 as section 5.3. In my view, this part is more relevant to different $\delta^{18}O$ signals at those two sites.

Following your suggestion, the discussion of topographic condition was moved to section 6 in the revision.

The authors seem to indicate that Dasuopu in the western Himalayas is influenced more by the westerlies, while East Rongbuk in the eastern Himalayas is influenced more by the summer monsoon. In this case, the increasing accumulation in East Rongbuk versus decreasing accumulation in Dasuopu reflects increasing monsoon versus decreasing westerlies in the past 200 years. Have you compared this finding with other studies about the interplay between the westerlies and Indian monsoon?

In the revision, we compared our results with other studies about the interplay between the westerlies and the Indian monsoon. We found that our results are consistent with other studies. For instance, the strong westerlies before the late 1930s and the intensifying ISM since the late 1930s obtained from the Himalayan ice core records are in agreement with a recent study (Joswiak et al., 2013).

Technical corrections

P1873 L6, ER and Xixiabangma are considered in the high central Himalayas, but P1877, ER and Xixiabangma are considered as the Eastern Himalayas and the western Himalayas, respectively. Which one is right?

Apologise for this confusion. In the revision, we define “western Himalayas” as the region where seasonal distribution of precipitation is bimodal and “eastern Himalayas” as the region where seasonal distribution of precipitation is unimodal. Based on this criterion, we demarcate the boundary nearby Mt. Qomolangma (Everest) as shown in Fig. 4. So to the west of Mt. Qomolangma (Everest) is defined as “western Himalayas” and to the east of Mt. Qomolangma (Everest) as “eastern Himalayas”.

P1874 L6-10, “Precipitation patterns…and accumulation rate records” can be deleted, as the data will be elaborated in Section 3. Besides, the introduction of data here without a scientific background for transition appears abrupt.

Changes have been made accordingly in the revision.

P1875 L3, please give reference to “Western Disturbances”. L8, remove “annually-dated”, ‘cause it is said later in L13 that “..ice core was annually dated to…”

A reference about “Western Disturbances” was included in the revision.

P1877 How is the western and eastern Himalayas divided? How do you define the central, western and eastern Himalayas? As Dingri and Nylam stations are very close to each other. If such a division is provided with some reference, the readers will be more convinced of the content.

In the revision, we gave a demarcation for the western and eastern Himalayas. The central Himalayas is not defined because it’s not necessary to define the borderline of the central Himalayas.

P1879 L11-12, “In order to further decipher the relationship between…and…and…, correlation coefficients between…and…and…are included in Table 2”

Apologise for this confusion. We have reworded this sentence in the revision.

L26-29, “The above correlation analysis results suggest that the relationship between…and…and…exists, but the relationship is vague for the Dasuopu core”. Description of the relationship is a bit confusing. By looking at Table 2, I think the authors are talking about "…the relationship between and among…". Or please rephrase to clarify "the relationship".

Apologise for this confusion, and changes have been made accordingly in the revision.

P1881 L27-28, "…convection activity is stronger over the western ISM region…"

Changes have been made accordingly in the revision.

P1882 L5 remove "both"

Changes have been made accordingly in the revision.

L7 "pronounced"

Changes have been made accordingly in the revision.

P1890 L16,delete 'that' at the beginning of the line;

Changes have been made accordingly in the revision.

L16-18, what does 'all Indian summer monsoon region and its sub-regions' refer to? Why is 'the middle-northern India' not a 'sub-region' of the Indian summer monsoon? Please rephrase the sentence.

"All Indian summer monsoon region" indicates the whole India. "Indian sub-regions" indicates the North East India (NEI), the North central India (NCI), the North West India (NWI), the North Mountainous India (NMI), the West Peninsular India (WPI), the East Peninsular India (EPI) and the South Peninsular India (SPI) as defined by Sontakke et al (2008). We have rephrased the content in the revision.

Figures:

Figure 3 precipitation seasonality should be based on the same duration to ensure the same climatic background. I thin the period from Jan, 1973 to Jan, 2011 would suffice to yield cliamtolgoy.

The figure was redrawn following this suggestion.

Figure 4 sold circle should be marked with a different mark. The current presentation is likely to be merged with the grey shadows.

Changes have been made accordingly in the revision.

Figure 5 please rephrase the caption as the current one is hard to comprehend.

Changes have been made accordingly in the revision.

Figure 6 The data source is unclear here. In the text, the authors first indicated that the "sensible heat net flux" is downloaded from NOAA/ESRL PSD. While later in the text, the authors indicated that the "sensible heat net flux…was computed using the …reanalysis data…' Are they of the same parameter? How is the sensible heat net flux computed, please specify?

Apologise for this confusion. Yes they are the same parameter.

We downloaded the "sensible heat net flux" data from NOAA/ESRL PSD as a grid-points data and calculated summer mean "sensible heat net flux" parameter over the specific regions, such as the Tibetan Plateau and Iran Plateau. The content has been deleted in the revision.

Additionally, figure captions are not consistent throughout, and some legend may need reorganization to ensure readability and avoid ambiguity.

Yes we have rephrased figure captions for consistency in the revision.

Sometimes the subtitles are before the subject, while other times they are placed after the subject.

Please be consistent in organizing the caption in one paper.

Yes we have reorganized the captions in the revision.

The usage of brackets is ambiguous. In most cases, it intends to explain and/or supplement the word before. While in other cases, it goes parallel and is replaceable with the word before. For the latter case, I suggest using slashes.

Changes have been made accordingly in the revision.

References

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Zhang, D., Qin, D., Hou, S., Kang, S., Ren, J., and Mayewski, P. A.: Climatic significance of $\delta^{18}O$ records from an 80.36 m ice core in the East Rongbuk Glacier, Mount Qomolangma (Everest), Science in China (series D), 48(2), 266-272, 2005.

Tables and Figures in the revision

Table 1. Pearson correlation coefficients between the Himalayan ice core records ($\delta^{18}O$ and accumulation rate) and the summer monsoon rainfall of four Indian homogenous rainfall regions north of 21ºN (NEI, NCI, NWI and NMI) since 1813 AD.

	NEI	NCI	NWI	NMI	ER-accum	DSP-accum	ER-$\delta^{18}O$	DSP-$\delta^{18}O$
NEI	1							
NCI	0.19[b]	1						
NWI	-0.17[b]	0.46[a]	1					
NMI	0.01	0.54[a]	0.62[a]	1				
ER-accum	-0.10	0.02	0.20[b]	0.00	1			
DSP-accumu	0.01	0.01	-0.09	0.02	-0.31[a]	1		
ER-$\delta^{18}O$	-0.12	0.03	0.02	0.01	0.01	0.10	1	
DSP-$\delta^{18}O$	-0.06	-0.25[a]	-0.02	-0.15[c]	0.28[a]	-0.39[a]	0.16[b]	1

Note: 2-tailed test of significance is used. a: 99% confidence level; b: 95% confidence level; c: 90% confidence level. ER: East Rongbuk; DSP: Dasuopu.

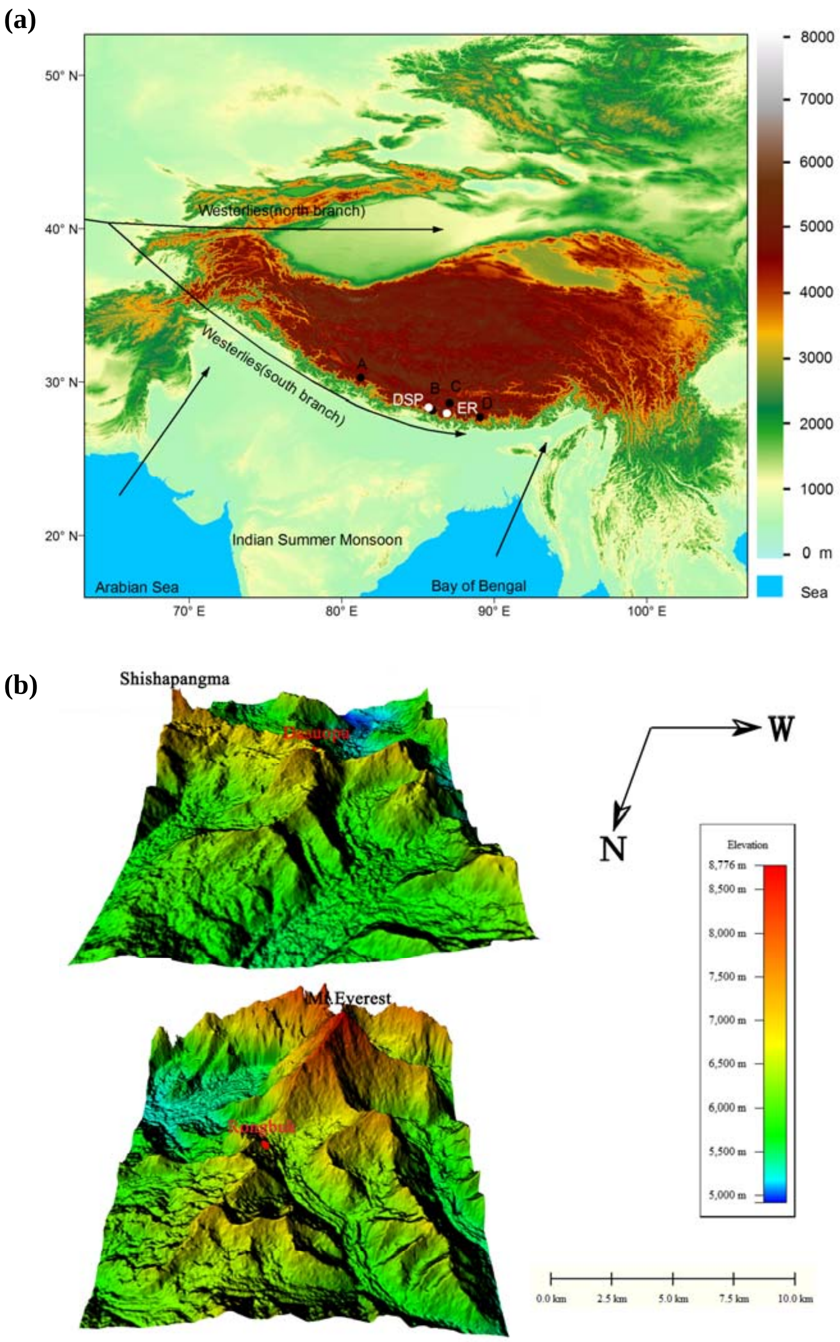

Figure 1. Atmospheric circulation systems over the study area (a), and three-dimensional topographic maps of the Dasuopu and East Rongbuk glaciers (b). Black solid circles indicate weather stations (A: Pulan; B: Nyalam; C: Dingri; D: Pali), and the white solid circles are the Dasuopu and ER ice core drilling sites. Digital elevation model (DEM) data is from ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) Global DEM with 30 m resolution.

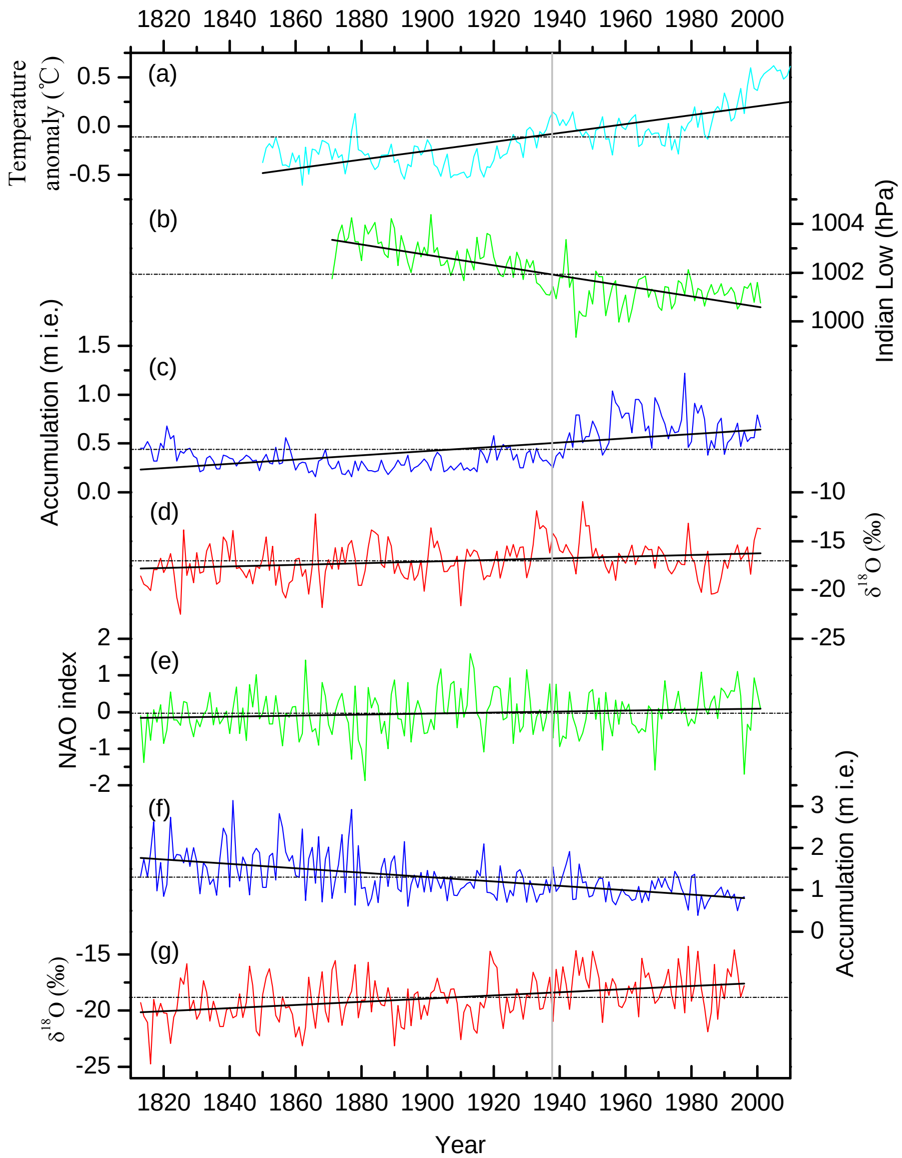

Figure 2. Variations of (a) Northern Hemisphere annual temperature anomaly (Jones et al., 2013), (b) the Indian Low intensity, (c) the ER annual accumulation rate, (d) the annual mean ER $\delta^{18}O$, (e) the non-monsoon season NAO index (Luterbacher et al., 2002), (f) the Dasuopu annual accumulation rate, and (g) the annual mean Dasuopu $\delta^{18}O$ since 1813 AD. The short dash dot lines are the averages of each series, and the bold lines are their linear trends. The vertical grey line indicates the boundary between the weak ISM period before the late 1930s (the year 1938) and the intensifying ISM period after the late 1930s. We choose the year 1938 as a boundary because the ER accumulation rate started to increase significantly since 1938.

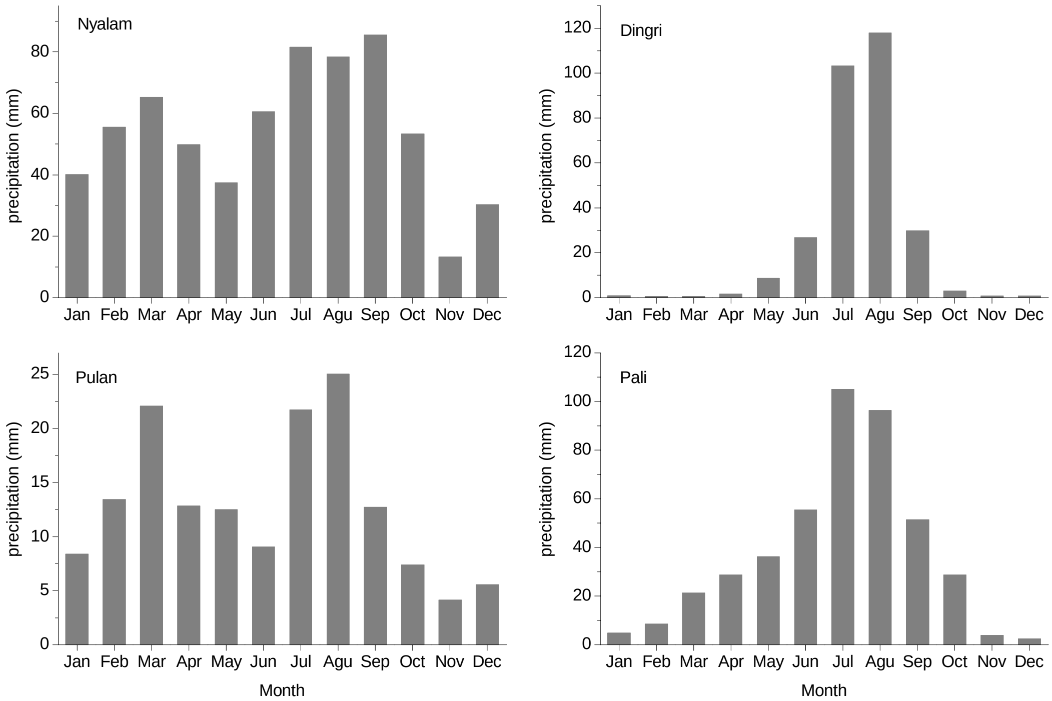

Figure 3. Monthly long term mean of precipitation at four weather stations along the Himalayas (Nyalam, Pulan, Dingri and Pali). Seasonal distribution of precipitation is calculated based on the meteorological data observed from January 1973 to January 2011.

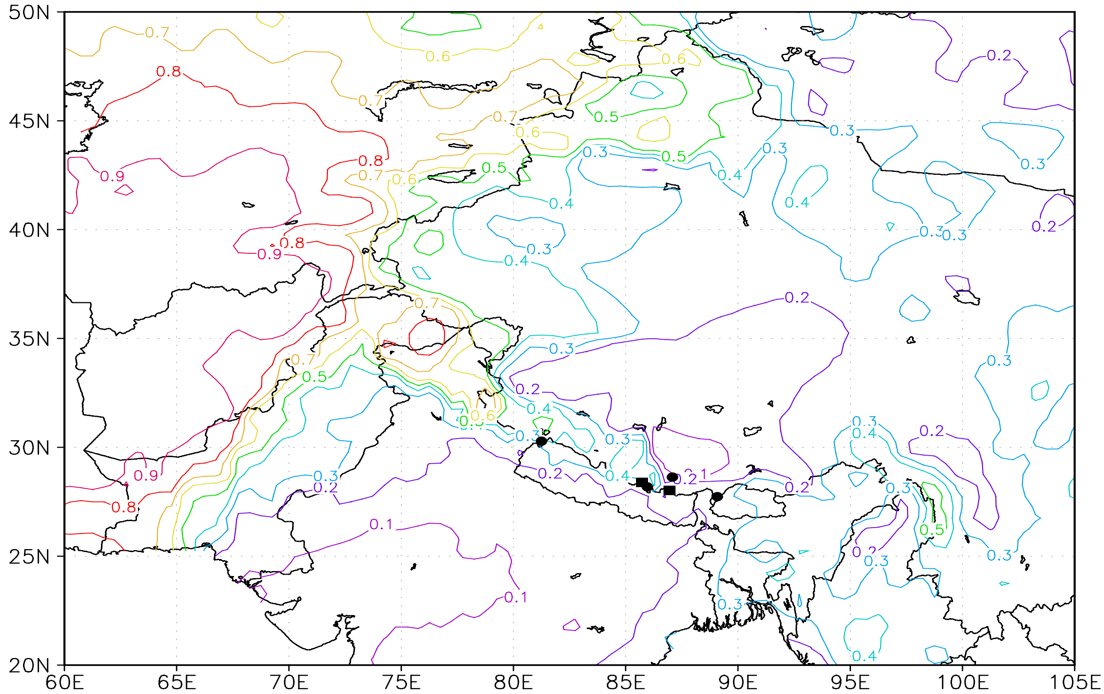

Figure 4. Map showing the non-monsoon season precipitation ratios to annual precipitation (October-May/annual) along the Himalayas. Reanalysis data are from the monthly long term mean (1981-2010) precipitation data with a 0.5ºx0.5º resolution from the Global Precipitation Climatology Centre (GPCC). Filled black circles are the four weather stations along the Himalayas (from left to right: Pulan, Nyalam, Dingri and Pali). The non-monsoon precipitation ratios at the Himalayan stations are generally consistent with those calculated from the GPCC data. The filled rectangles are Dasuopu and East Rongbuk ice cores sites.

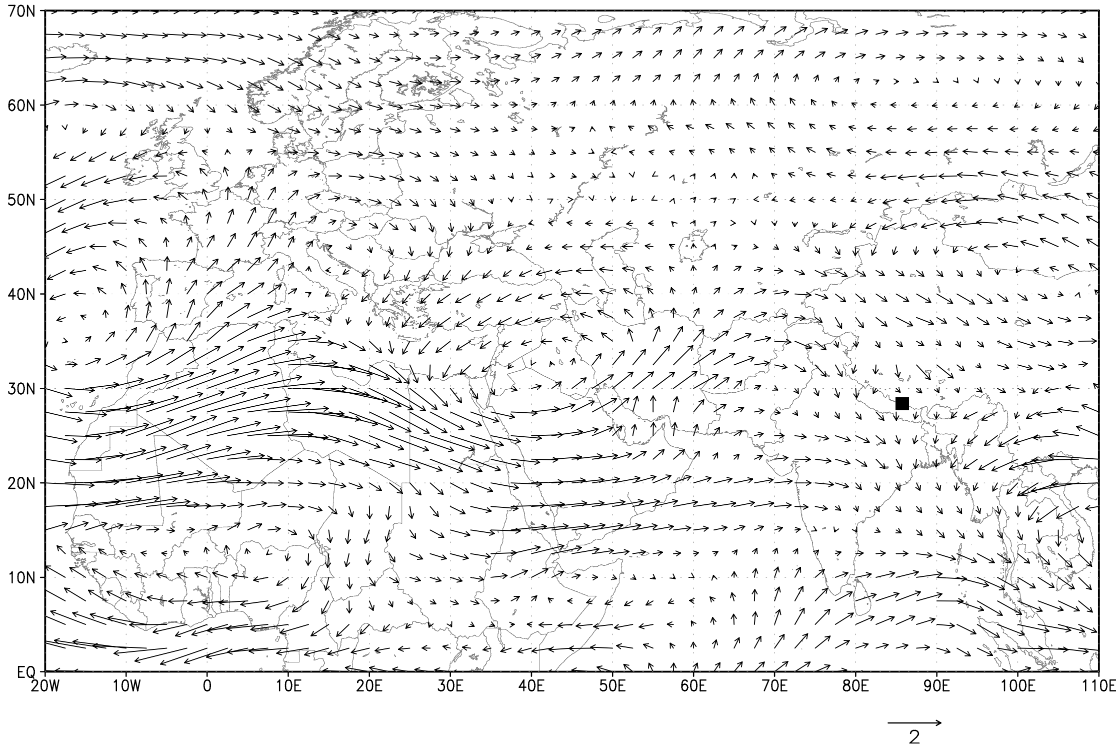

Figure 5. Composite analysis of moisture flux (multiplying by wind vector and specific humidity) at 400 hPa level during the winter-spring season (February to April) between years with higher and lower Dasuopu accumulation rate (higher-lower). The filled rectangle indicates the Dasuopu core drilling site.

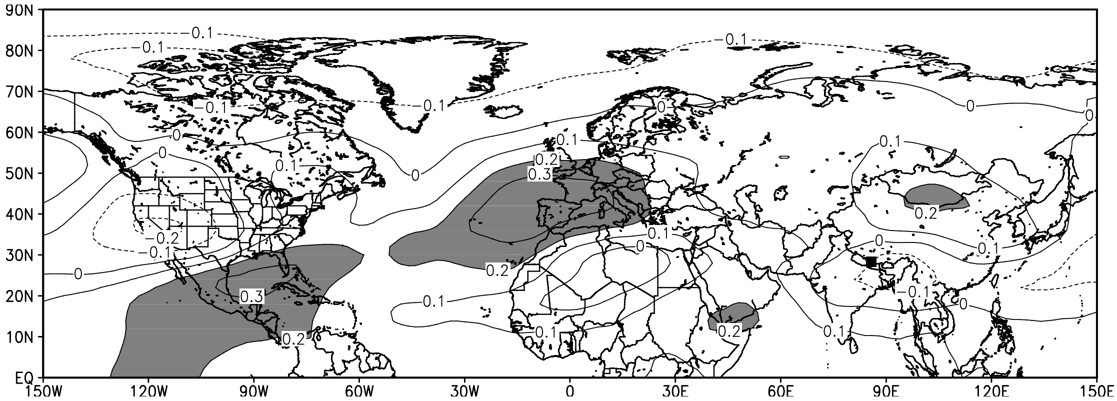

Figure 6. Correlation coefficients between the annual mean Dasuopu $\delta^{18}O$ and mean air temperature during the non-monsoon season (October to May) at 400 hPa level since 1871. The monthly air temperature data with 2.0º×2.0º resolution are from the twentieth century reanalysis (V2). Grey shadow indicates correlation significance at 95% confidence level. The filled rectangle indicates the Dasuopu core drilling site.

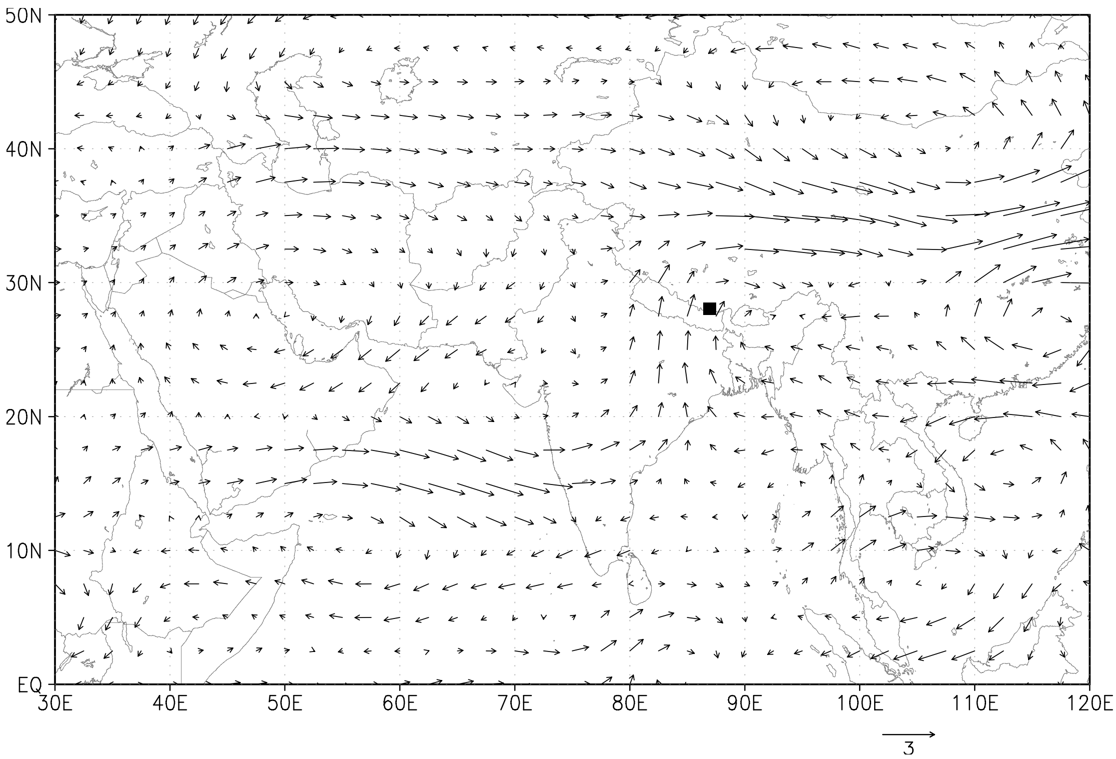

Figure 7. Composite analysis of summer mean (June to September) moisture flux (multiplying by wind vector and specific humidity) at 400 hPa level between years with higher and lower ER accumulation (higher minus lower). The filled rectangle indicates the ER core drilling site.

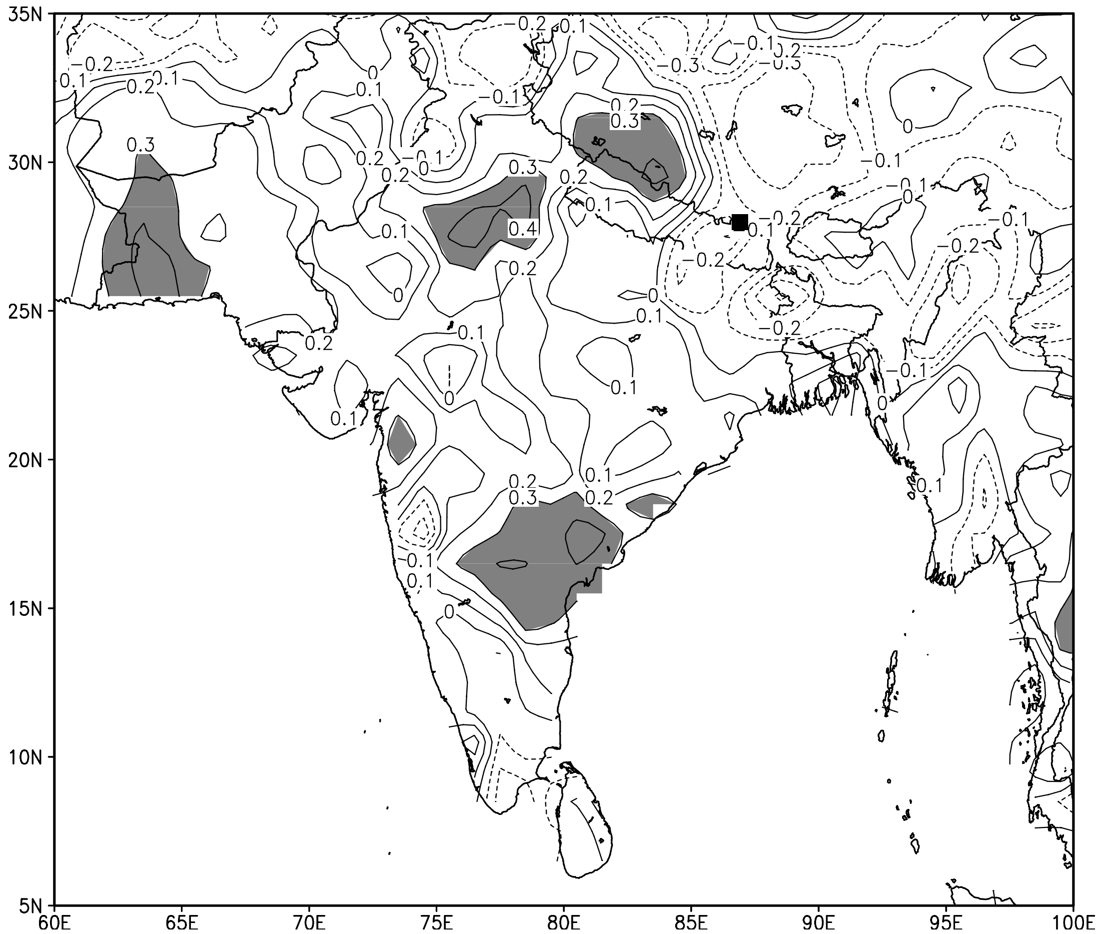

Figure 8. Correlation coefficients between the ER accumulation rate and summer (June to September) precipitation over the period 1951-2001. Grey shadow indicates correlation significance at 95% confidence level. The filled rectangle indicates the ER core drilling site. Summer precipitation data is from the Global Precipitation Climatology Centre (GPCC) monthly precipitation dataset from 1951-present with 1.0º×1.0º resolution (available at http://gpcc.dwd.de).

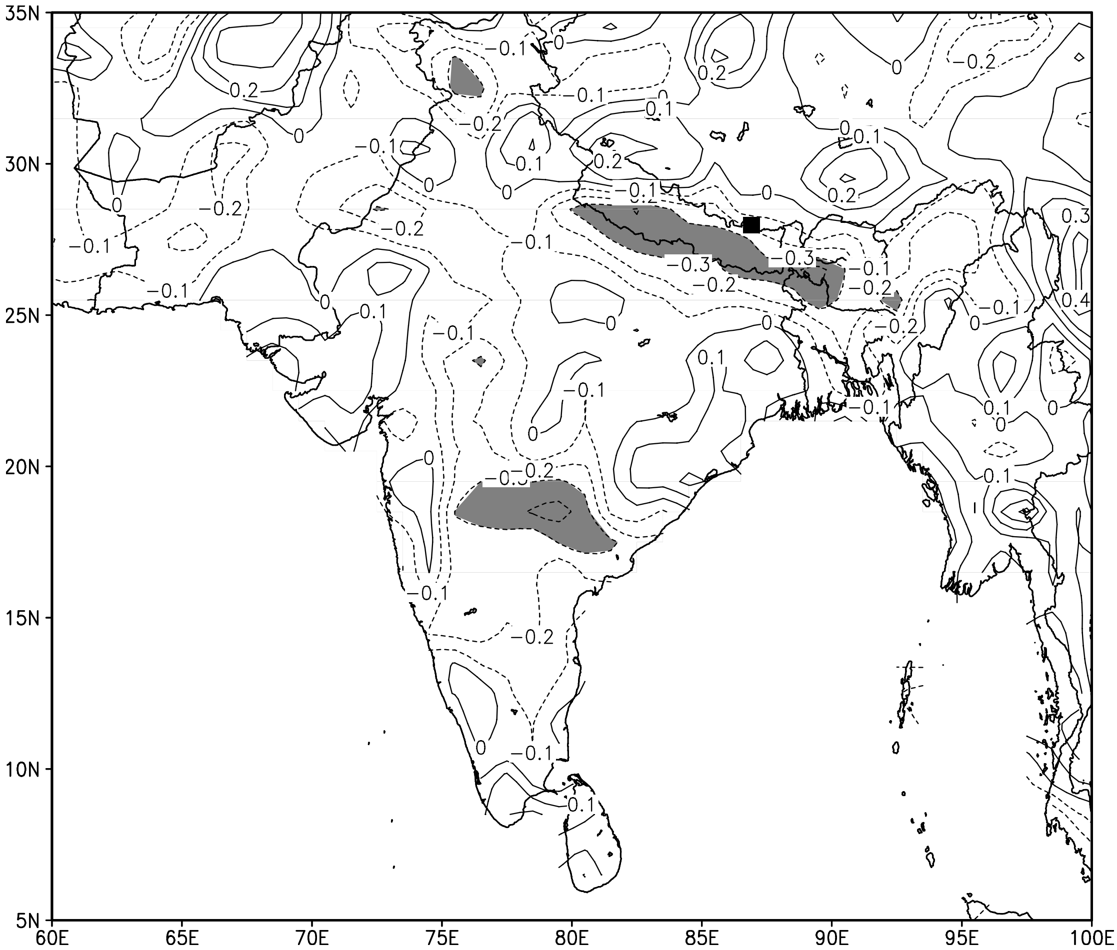

Fig. 9 Correlation coefficients between the ER $\delta^{18}O$ record and summer (June-September) precipitation over the period 1951-2001. Grey shadow indicates correlation significance at 95% confidence level. The filled rectangle indicates the ER core drilling site. Summer precipitation data is from the Global Precipitation Climatology Centre (GPCC) monthly precipitation dataset from 1951-present with 1.0º×1.0º resolution (available at http://gpcc.dwd.de).