***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 #1

1 General comments

The paper aims at explaining why the $\delta^{18}O$ records from the Dasuopu and East Rongbuk glaciers are interpreted differently. This is an interesting aim. Beyond the interpretation of these specific ice cores, this aim is of interest for a broader community since it may help better understand the relative effect of temperature and precipitation in controlling $\delta^{18}O$ in tropical ice cores.

The paper is well written.

However, I'm not sure I understand how the authors get to their conclusion, it looks like several steps in the reasoning are missing and in contrast I don't understand how some parts of the paper relate to the reasoning. The take-home message and the reasoning to get there should be explained more clearly as explained in specific comments.

I think the paper is relevant to the Cryosphere but needs revision.

We agree that some parts concerning to the spatial fluctuations of the Indian summer monsoon (the north-south and west-east seesaws) 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, and as a consequence, we give just a brief response to some comments related to the deleted part.

2 Specific comments

2.1 Clarify the goals and the different steps of the reasoning

- **Clarify the take-home message.** Based on what I understand of the paper, the take-home message of the paper is that Dasuopu gets more precipitation from moisture advected by the westerlies, which makes it more sensitive to temperature, whereas East Rongbuk gets more precipitation from moisture advected by the ISM flow, which makes it more sensitive to precipitation amount. If this is not your take-home message, then it really needs clarification. Below my comments assume that I understand the take-home message correctly.

Yes this is the take-home message in our manuscript.

- P 1880 | 21 to 1882 | 2: **why use OLR anomalies rather than precipitation anomalies? What is the goal or added value of using OLR?** If the goal is to show spatial covariations in precipitation variability, why not just use precipitation?

  Precipitation observations over oceans are sparse. Therefore, we made use of the satellite OLR data, which cover oceans, to show the spatial precipitation patterns. In fact, we drew a figure from the monthly NOAA CPC Merged Analysis Precipitation (CMAP) dataset during the period Jan 1979 to July 2008 (not shown here), and found that the precipitation anomalies are similar to the OLR anomalies.

- **What is the use of section 5.2 on seesaws?**
  - What are the implications of the existence of North-South and West-East seesaws for the interpretation of ice core records? Does this have any role on the relative proportion of moisture from the westerlies or from the ISM? Section 5.2 looks useless and may be removed unless its link with the goal of the paper is clarified.
  - To relate to the goal of the paper, it would be more interesting to investigate the link between these seesaws and the ice core records, e.g. calculate correlations between indexes of the North-South and West-East seesaws on the one hand and accumulation rate and $\delta^{18}O$ at ER and Dasuopu on the other hand. If $\delta^{18}O$ at ER does record one or both of these seesaws whereas Dasuopu does not, then it supports your conclusion.
  - The discussion on the causes of the seesaws is interesting, but how useful is it to address the question of the interpretation of stable isotopes in ice cores? I'm not sure this discussion belongs to this paper unless understanding the causes of these seesaws is really useful to understand the ice core records. Otherwise, this discussion should be moved into another paper.
  - Some of the discussion is on intra-seasonal time scales. How relevant is it for precipitation variability at the inter-annual time scale? Also, clarify for each process or for each model of variability whether it is involved in intraseasonal or inter-annual time scales.
  - Have the ISM seesaws any influence on the relative influence of the westerlies and of the ISM on precipitation falling on the ice cores? May some of the inter-annual variability in $\delta^{18}O$ at ER or at Dasuopu be associated with variations in this relative influence?
  - I think the core of the paper is in section 5.1: that's where you argue for the difference of moisture origin on the 2 cores. The relevance of sections 4.2 and 5.2 is not clear. Again in conclusion: p 1889 | 10-25: how does it contribute to answering your initial question?

  All the six comments above focus on what's the relevance of the ISM seesaws to the goals of the paper. Below we give a joint reply to these comments.

The winter moisture transport by the westerlies is not influenced by the ISM seesaws because the westerlies prevail in winter, while the ISM dominates in summer over our study area (the central Himalayas).

Inter-annual ISM moisture transport may be little influenced by the ISM intra-seasonal oscillations because the mechanism for the former is likely different from that for the latter.

Following the comments, we defined the ISM north-south seesaw index as the difference between the standardization of SPI and NEI precipitation (SPI minus NEI), and the ISM west-east seesaw index as the difference between the standardization of NWI and NEI precipitation (NWI minus NEI). We calculated correlations between the ISM seesaws indexes and the Himalayan ice core records (accumulation rate and $\delta^{18}O$) and found there are no significant correlations between them, suggesting a minor influence of the ISM seesaws on the Himalayan ice core records.

As a result, we decide to delete the content concerning to the ISM seesaws (Sections 4.2 and 5.2) in the revision.

- The authors investigated the variability in ISM precipitation, because they argue that variability in ISM precipitation influence $\delta^{18}O$ at ER. **But why focusing on only one half of the problem?** They argue that winter westerlies and /or temperature influence $\delta^{18}O$ at Dasuopu: **why not investigating the inter-annual variability in the westerlies and /or temperature**, with as much detail as investigating the ISM precip? Why going in more details for the controls at ER than for the controls at Dasuopu?

P 1890 | 19: “spatial patterns of ISM precipitation should be taken into account”: and what about the spatial patterns of the westerlies, don’t they need to be taken into account as well?

The Dasuopu isotopic record ($\delta^{18}O$ or δD) was interpreted as a proxy for temperature in previous papers (e.g., Thompson et al., 2000). So we ignored a detailed discussion of the temperature control on the Dasuopu isotopic record. Later it’s indicated that Dasuopu receives most precipitation during the ISM season, and the isotopic variations of Dasuopu ice core are ascribed to temperature changes at mean condensation level (Davis et al., 2005). If precipitation falling at Dasuopu happens mostly during the ISM season, it’s hard to exclude the amount effect on the isotopic composition of the monsoon-induced precipitation at Dasuopu. This prompted our interest for a further investigation on the factors controling the precipitation stable isotopes at Dasuopu. We identified the possible influence of the westerlies on the Dasuopu $\delta^{18}O$, as shown in Figs. 5 and 6 of the revision. We want to point out that this is not the final word, and more works should be paid on this issue.

- The authors discuss the different moisture origins and the ISM modes of variability. But **an important step is missing before we can understand the $\delta^{18}O$ signal: for a given moisture origin and in the context of given modes of variability, what does $\delta^{18}O$ record?**

- Even if ER receives most of its precip from the ISM and that the ISM varies at the inter-annual scale according the seesaws, is it proven that $\delta^{18}O$ records variations in ISM? Does your record or data published in the literature support that? And if so, the precipitation where and when, by what mechanisms?

- Even if Dasuopu receives moisture from the westerlies, is it proven that $\delta^{18}O$ will record temperature? And if so, the temperature when and where, at what time scales?

For the interpretation of both ice cores, it would be useful to check the link between $\delta^{18}O$ at ER and ISM precipitation/seesaws and between $\delta^{18}O$ at Dasuopu and temperature in a region and season to be defined.

You can also refer to previous studies. For example, daily isotopic data has been collected and analyzed to try and better understand $\delta^{18}O$ at the process scale (e.g. Gao et al. (2011)).

Yes it's really necessary to clarify what the Himalayan ice-core $\delta^{18}O$ records stand for. This is also our purpose of this manuscript. In the revision, we firstly justify the influence of the precipitation seasonality over the Himalayas, and then investigate the climatological significance of the Himalayan $\delta^{18}O$ records.

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. The Dasuopu 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 Dasuopu 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) (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.

To examine the control of winter westerlies on the Dasuopu precipitation, we analyzed the correlation between the Dasuopu accumulation rate and the winter-spring season (February to April) precipitation. We choose February-April as the winter-spring season because the non-monsoon precipitation peak occurs during these months (Fig. 3). Fig. 5 shows composite analysis of moisture flux at 400 hPa level during the winter-spring season between years with higher and lower Dasuopu accumulation rate (higher-lower). It is clear that the westerlies moisture originating in Atlantic Ocean passing through northern Africa, Arabia, Iran, Afghanistan, Pakistan and Tibetan Plateau is stronger when the Dasuopu accumulation rate is higher, and vice versa, suggesting that the Dasuopu precipitation is influenced significantly by the westerlies.

In addition, we calculated the correlation between the Dasuopu accumulation rate and the winter-spring season precipitation amount derived from the GPCC monthly precipitation data since 1951. However, no significantly positive correlation was found over the western Himalayas (figure not shown), which may be due to the recent increasing contributor of the ISM precipitation to the Dasuopu precipitation (we discuss it in section 7) or lacking of longer precipitation observation over the high Himalayas.

Finally, we calculated the correlation between the Dasuopu $\delta^{18}O$ record and mean air temperatures during the non-monsoon season at different pressure levels using the twentieth century reanalysis (V2) data, and identified a good positive correlation region over the Azores High area and its adjacent regions between the Dasuopu $\delta^{18}O$ record and air temperatures in the mid-low troposphere (from 850 to 300 hPa level). Moreover, the positive correlation region is stable at different pressure levels. Because the elevation of Dasuopu drilling site is high (7200 m above sea level), we just present the correlation coefficients at 400 hPa level as a demonstration, as shown in Fig. 6. Such a positive correlation may indicate a closely relationship between the North Atlantic Oscillation (NAO) and the Dasuopu $\delta^{18}O$ record. The high (low) air temperature over the Azores High region may imply the position of Azores High shifting northward (southward), corresponding to the northward (southward) shifting of the westerlies. When the mid-latitude westerlies move southward (northward), more (less) and colder (warmer) air masses can be transported eastward and be potentially captured in the Himalayas, probably leading to lower (higher) $\delta^{18}O$ value of the Dasuopu core. According to previous studies, there is a good positive correlation between the NAO index and the Northern Hemisphere temperature (Hurrell, 1996; Gimeno et al., 2003), which may explain why there is a good correlation between the Dasuopu $\delta^{18}O$ record and the Northern Hemisphere temperature (Thompson et al., 2000; Davis et al., 2005).

To further testify the dominant ISM control on the ER $\delta^{18}O$, the correlation between the ER accumulation rate and the ISM circulation was investigated (Figs. 7 and 8). Fig. 7 shows composite analysis of summer mean (June to September) moisture flux at 400 hPa level between years with higher and lower ER accumulation (higher minus lower). It is clear that the ISM moisture flux from the Arabian Sea, via northern central India, to the central Himalayas is stronger when the ER accumulation rate is higher, and vice versa, indicating that the precipitation at the ER core site is significantly influenced by the ISM moisture transport. In addition, the correlation between the ER accumulation rate and summer monsoon season precipitation is also analyzed based on the GPCC monthly precipitation data since 1951, as shown in Fig. 8. It is clear that the strongest positive correlation occurs over the northwestern region of India (i.e., the core region of the India Low), which is in agreement with the correlation analysis between the ER accumulation rate and the summer monsoon rainfalls over the four northern sub-India regions (Table 1). This suggests that precipitation at ER core site is mainly controlled by the large-scale ISM circulation.

The narrow band negative correlation region along the southern slope of Himalayas between the ER $\delta^{18}O$ and the summer precipitation (Fig. 9) doesn't overlap with the positive correlation region in the northwest India between the ER accumulation rate and the summer precipitation (Fig. 8). This suggests that the ER $\delta^{18}O$ is probably controlled by precipitation processes associated with deep convective activities over the southern slope of Himalayas due to its very steep topographic gradient, where the heavy isotopes in vapor are washed out strongly by intense precipitation processes.

2.2 What are the implications of this work?

- What are the implications of this work **for the interpretation of Dasuopu and East Rongbuk records?** What do you conclude from the $\delta^{18}O$ trends in terms of trends in temperature or in ISM precipitation? What do you conclude from the inter-annual variability of $\delta^{18}O$ in terms of inter-annual variability of temperature and ISM? Can some of the signal at one of these sites reflect the varying contribution of moisture from the westerlies and from the ISM?

If for example you are able to link the trends, inter-annual variability or some specific events of ER $\delta^{18}O$ to a seesaw of the ISM, then the analysis of the causes of these seesaws in section 5.2 may become relevant, because in this case you could attribute the ER $\delta^{18}O$ variations to various factors or forcings.

Clarifying the climatological significance of the Himalayan ice core records ($\delta^{18}O$ and accumulation rate) would have strong implications for future interpretations of ice core stable isotope records recovered from different climatological regimes of the Himalayas.

The Himalayas is located in the northern area of the Indian monsoon domain and in the southern part of the mid-latitude winter westerlies domain. The climate of the very high central Himalayas where the Dasuopu and ER ice cores were recovered may be very sensitive to activities of the ISM and the westerlies. In this paper, we find that the evolutions of the ISM and the westerlies over the Himalayas during the past two centuries can be recorded by the Himalayan ice core records (accumulation rate and $\delta^{18}O$).

The relatively low ER accumulation rate with small variation amplitude before the late 1930s is likely indicative of the ISM weakening. The remarkable increasing of the ER accumulation rate and the evident decrease of the ER $\delta^{18}O$ since the late 1930s may correspond to the ISM intensifying.

The very high Dasuopu accumulation rate with large variation amplitude before 1880s may indicate the strong westerlies activities over the central high Himalayas. Since the late 19^{th}

century, the gradually decrease in Dasuopu accumulation rate and increase in Dasuopu $\delta^{18}O$ may correspond to the gradually weakening of the westerlies over the central high Himalayas.

The overall increase (decrease) trend of the ER (Dasuopu) accumulation rate may hint the intensifying (weakening) of the Indian summer monsoon (winter westerlies) over the high central Himalayas, probably in response to the global warming since the Little Ice Age.

- What are the implications of this work **for the broader debate on the relative effect of temperature and precipitation in controlling $\delta^{18}O$ in tropical ice cores? Can this study be extended to other tropical ice cores?** For example, for a given ice core, can we assess the relative effect of temperature and precipitation controls based on a study of the origin of air masses? Can all tropical ice cores be classified into ER-type (recording precip) and Dasuopu type (recording temperature), and if so on what criterion would you do this classification?

From Fig. 4, we can conclude that the non-monsoon precipitation ratio in some mountain regions may be comparable to the summer monsoon precipitation ratio. Furthermore, the precipitation seasonality may vary with climate change. In tropical monsoon regions, the control factor on precipitation stable isotopes differs between in summer (precipitation amount) and in winter (temperature). Therefore, precipitation seasonality should be considered when interpreting isotopic records of ice cores or speleothems retrieved from the tropic monsoon regions. To evaluate the relative effect of temperature and precipitation in controlling isotopic composition in tropical ice cores, the precipitation seasonality should be first assessed.

2.3 Miscellaneous

- P 1872 | 11: “The north-south and west-east seesaws of the Indian Summer Monsoon (ISM) precipitation are primarily responsible for precipitation falling at the ER site”: do you mean “responsible for the inter-annual variability of the precipitation falling at the ER site”? Modes of variability cannot be not responsible for a precipitation amount, rather for a precipitation variability. Generally, I think this awkward wording reflects a confusion throughout the paper between the origin of precipitation and the sources of precipitation variability.

Yes we agree that the ISM seesaws would influence the inter-annual variability of precipitation falling at the ER site. In the revision, we deleted the content concerning to the ISM seesaws (Sections 4.2 and 5.2). This eliminates the confusion in the previous version of this manuscript.

- P 1872 | 5: “interpreted” -> “interpreted in the literature” or “interpreted in previous studies”.

Changes have been made accordingly in the revision.

- It's not clear what is your contribution in this paper: are you bringing new data? Or are you just reviewing previous studies and your contribution is to make new connections between them?

  Yes we try to make new connections between the Dasuopu and the ER ice core records.

- P 1873 | 27-28: "the large-scale circulation at the two sites are the same": really? I thought one of your conclusions was that ER was more influenced by the ISM…

  Apologise for this confusion. We intend to point out that the large-scale circulation systems (the Indian summer monsoon and the westerlies) at the ER and the Dasuopu drilling sites are the same, but local circulation conditions may be different due to their local topographic features.

- P 1875 | 16 and | 21: start new paragraph

  Changes have been made accordingly in the revision.

- P 1876 | 13 to 1877 | 4: this is not about seasonal distribution, this should be in an earlier subsection of 4.

  Changes have been made accordingly in the revision.

- 1878 | 7: "spatial variability on intra-seasonal to inter-annual scales": Do you mean rather "temporal variability"? Normally spatial variability can be seen at different spatial scales (meso, regional, continental) whereas temporal variability can be seen at different temporal scales (intra-seaosnal, inter-annual…)

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

- Throughout the paper, it would be useful in the discussion to separate the effects of trends and the effect of inter-annual variability. Do the correlations hold after detrending the time series?

  Yes we have separated the effects of trends and the effect of inter-annual variability in the revision. The correlations hold after detrending linearly (Table 1).

- P 1887 | 7-8: “larger accumulation rate … indicator of the different precipitation seasonality”: I don’t understand, there is no a priori link between precip amount and precip seasonality.

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

- P 1887 | 24 “higher elevations … low latitude source regions” but p 1888 | 4-8: “high elevations … winter time precipitation … western disturbance” ->inconsistent? So is the ISM expected to have more influence at high or low elevations?

The case for Mt. Logan is inconsistent with the case for the central Himalayas. As to Mt. Logan, the moisture source of the high altitudes is different from that of the low altitudes. As to the central Himalayas, the moisture sources of the high and low altitudes are the same (westerlies), but precipitation amount may be much higher in the high altitudes than that in the low altitudes.

Dhar and Rakhecha (1981) indicated that the zones of maximum ISM rainfall occur near the foothills at an elevation of 2.0 to 2.4 km. Beyond the elevation, the ISM rainfall decreases continuously with rising elevation until the great Himalayan range is reached. This indicates that the ISM precipitation decreases significantly with rising elevation in the southern slope of Himalayas.

- P 1888 | 20: “restricted by convection height of the ISM”: there is nothing like a convection height of the ISM. In the context of the ISM, there are some convective systems that have some height. And I cannot see the link between the height of these convective systems and “monsoonal precipitation amount” “in the high elevations of Himalayas”. The rain that is falling on the Himalayas does not come from convective systems that shower the mountains from above. There are plenty of convective systems that appear and disappear everywhere where there is enough moisture and convective instability, and this leads to rain at the surface whatever the height of these convective systems. I would remove this argument.

Yes the discussion about the convective height and its potential influence on precipitation amount at different heights was removed in the revision.

- P 1888 | 15: “more observations on moisture transport … are needed”. **Specifically, what kind of data do you need?** Moisture transport is not directly observable. Do you need reanalysis data to calculate moisture budgets (e.g. review by Gimeno et al. (2012))? Do you need water vapor measurements to give information on the moisture origin (e.g. Lee et al. (2012))? If so, this is already available and it should be highlighted as precious to exploit in future work. If you need more data that are not yet available, it’s a good opportunity to encourage such data collection, but in this case you need to be specific.

In the revision, we include moisture flux using reanalysis data for identifying moisture transport (Figs. 5 and 7). Specially, we emphasize the importance of measurement of precipitation amount in the high Himalayas to realize the contribution of the precipitation in the non-monsoon season to the annual precipitation.

- P 1890 | 19-20: how should they be taken into account? What is the strategy? For example, if a map of the proportion of precipitation coming from the westerlies and from the ISM available, would it be enough to know how to interpret any Himalayan ice core? Or what specific information do you need to interpret an ice core properly?

Though it's reasonable for a better interpretation of any Himayayan ice core, given a known proportion of precipitation coming from the westerlies and from the ISM, it's not straightforward, because various other factors might be involved in a nonlinear degree.

3 Technical corrections

- P 1882 | 7: "variations and trends" -> "variations in trends"?
- P 1889 | 3: "implying" -> "suggesting"

Changes have been made accordingly in the revision.

References

Davis, M. E., Thompson, L. G., Yao, T., and Wang, N.: Forcing of the Asian monsoon on the Tibetan Plateau: Evidence from high-resolution ice core and tropical coral records, J. Geophys. Res., 110, D04101, doi:10.1029/2004JD004933, 2005.

Dhar, O. N., and Rakhecha, P.R.: The effect of elevation on monsoon rainfall distribution in the central Himalayas, in Monsoon dynamics, eds., Lighthill, J., and Pearce, R.P., New York, Cambridge University Press, p.253-260, 1981.

Gimeno, L., Torre, L., Nieto, R., García, R., Hernández, E., and Ribera, P.: Changes in the relationship NAO-Northern hemisphere temperature due to solar activity, Earth Planet. Sci. Lett., 206, 15-20, 2003.

Hurrell, J. W.: Influence of variations in extratropical wintertime teleconnections on Norther Hemisphere temperature, Geophys. Res. Lett., 23, 665-668, 1996.

Thompson, L. G., Yao, T., Mosley-thompson, E., Davis, M. E., Henderson, K. A., and Lin, P. N.: A high-resolution millennial record of the south Asian monsoon from Himalayan ice cores, Science, 289, 1916-1919, 2000

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.

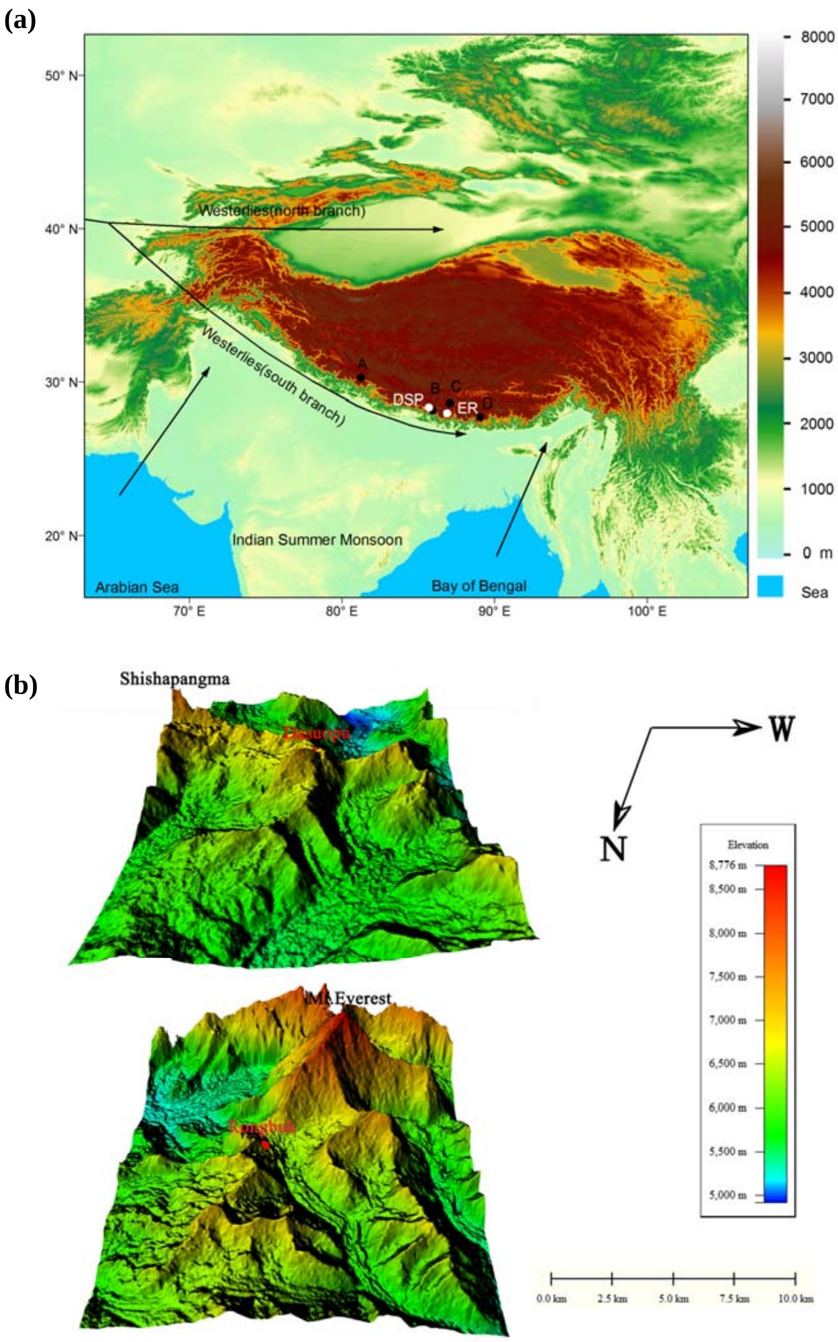

Figure 1. Atmospheric circulation systems over the study area (a), and three-dimensional topographic maps of the Dasuopu and East Rongbuk glaciers (b). Black solid circles indicate weather stations (A: Pulan; B: Nyalam; C: Dingri; D: Pali), and the white solid circles are the Dasuopu and ER ice core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

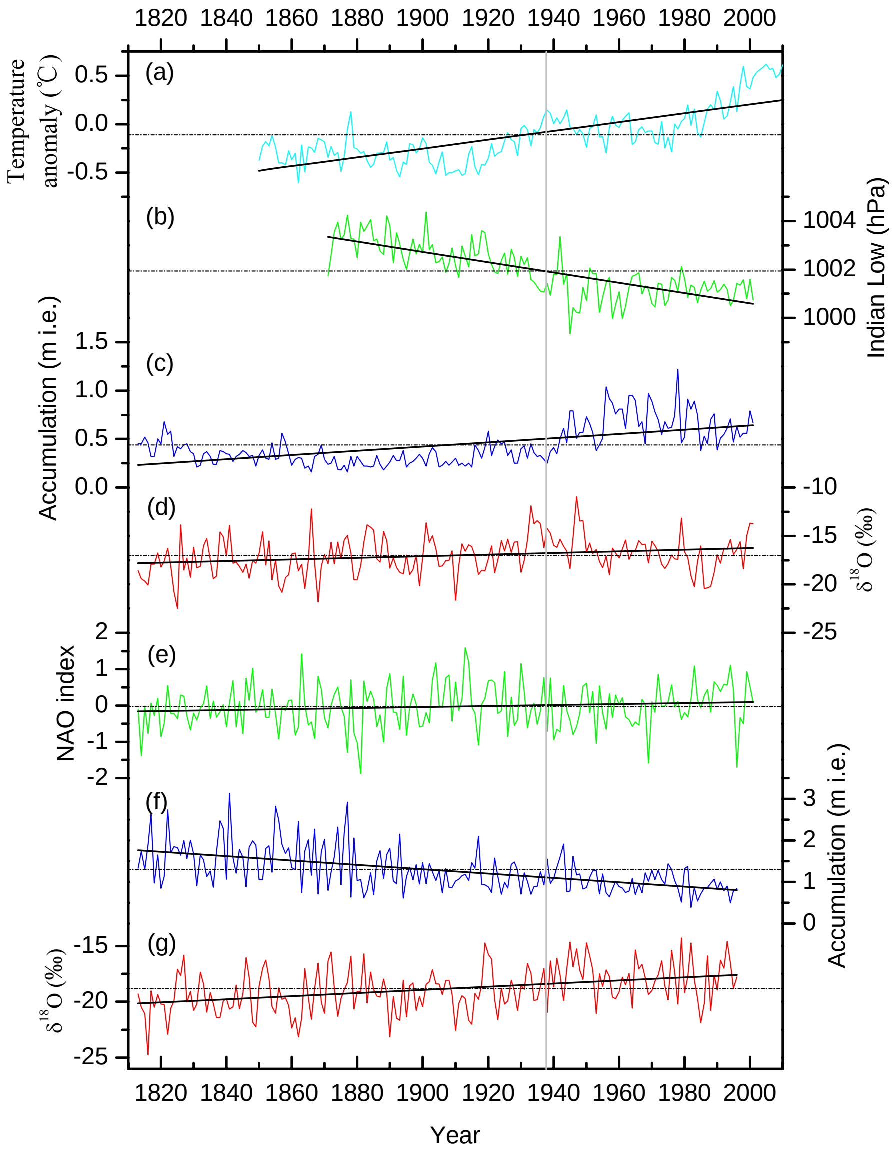

Figure 2. Variations of (a) Northern Hemisphere annual temperature anomaly (Jones et al., 2013), (b) the Indian Low intensity, (c) the ER annual accumulation rate, (d) the annual mean ER $\delta^{18}O$, (e) the non-monsoon season NAO index (Luterbacher et al., 2002), (f) the Dasuopu annual accumulation 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.

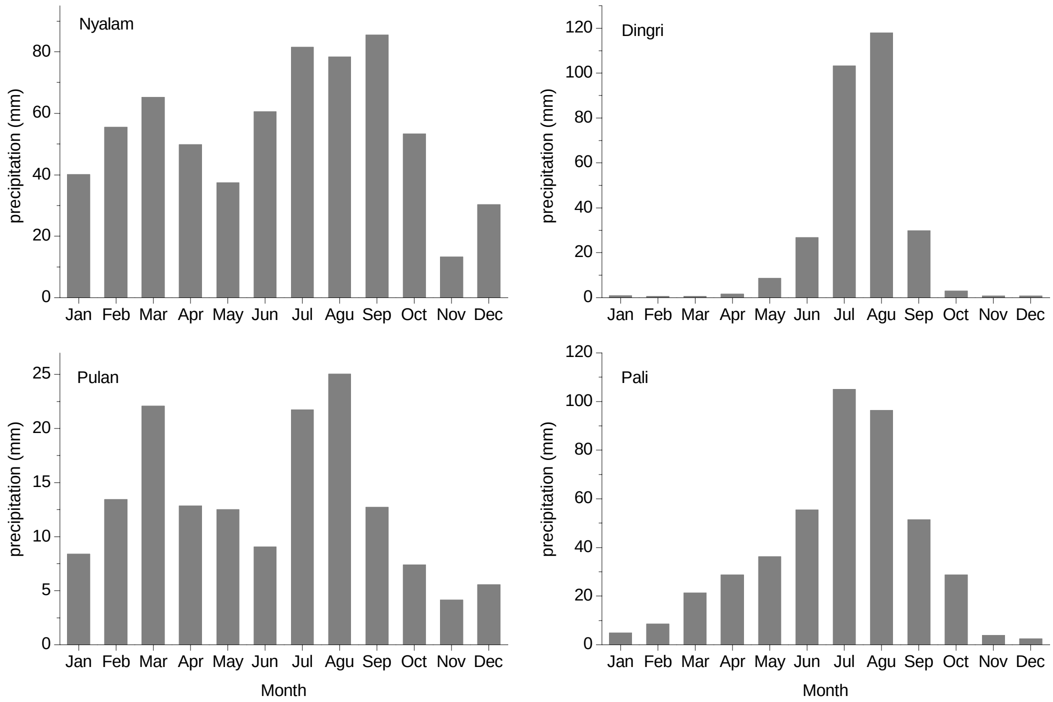

Figure 3. Monthly long term mean of precipitation at four weather stations along the Himalayas (Nyalam, Pulan, Dingri and Pali). Seasonal distribution of precipitation is calculated based on the meteorological data observed from January 1973 to January 2011.

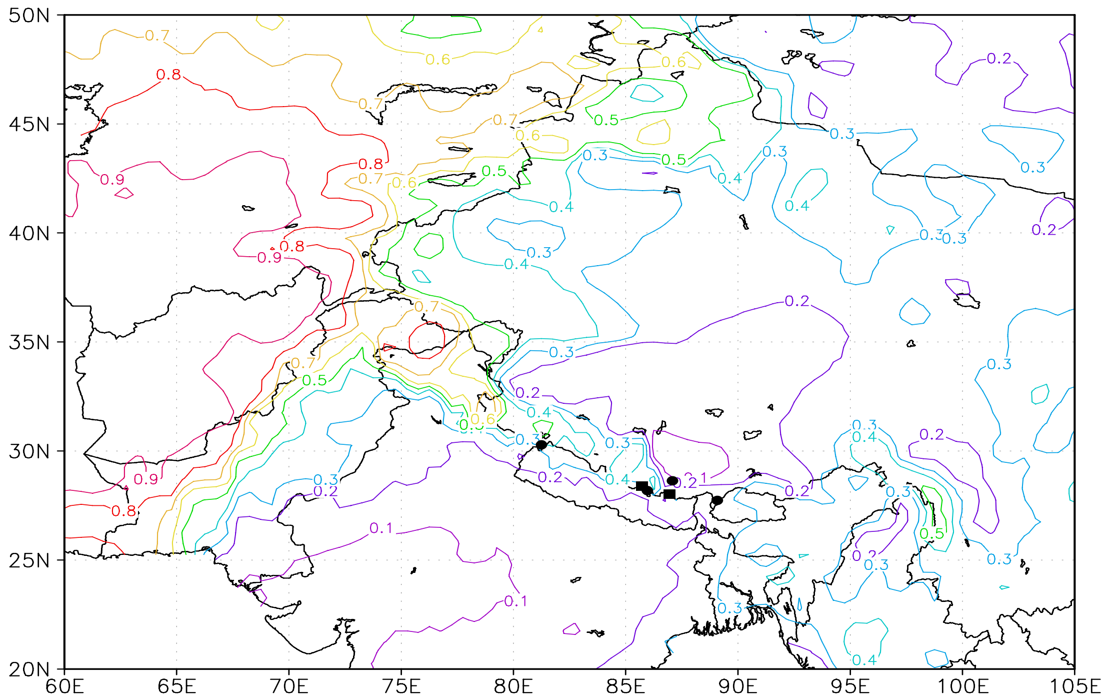

Figure 4. Map showing the non-monsoon season precipitation ratios to annual precipitation (October-May/annual) along the Himalayas. Reanalysis data are from the monthly long term mean (1981-2010) precipitation data with a 0.5°x0.5° resolution from the Global Precipitation Climatology Centre (GPCC). Filled 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.

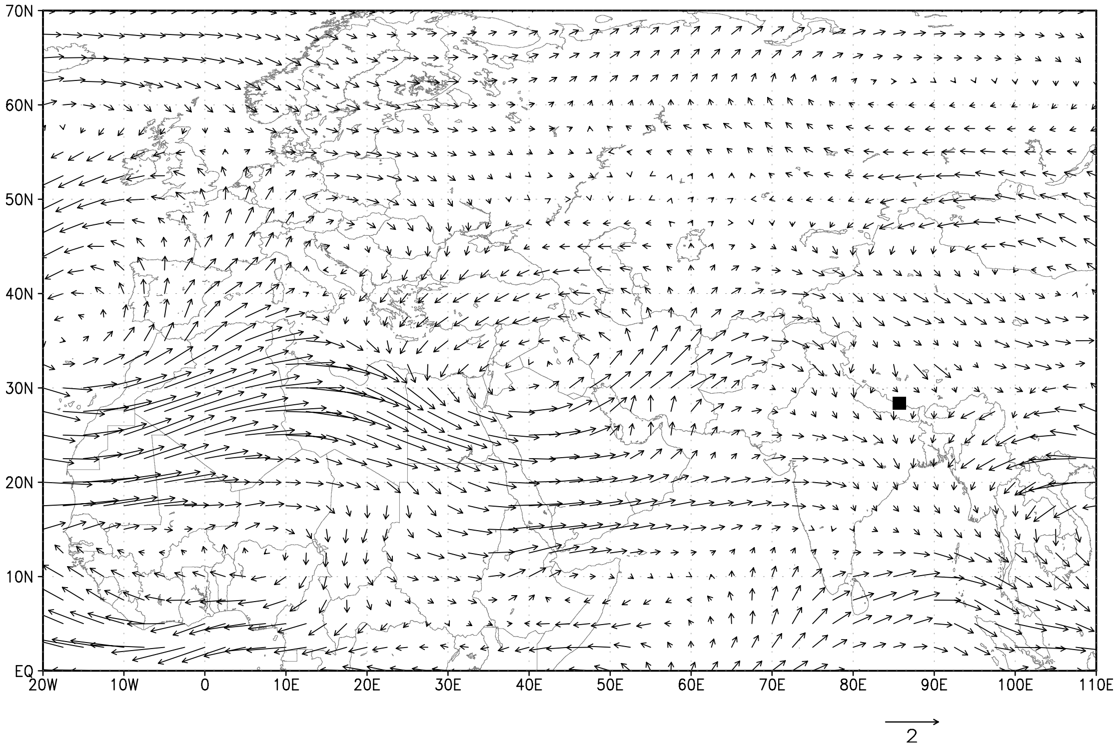

Figure 5. Composite analysis of moisture flux (multiplying by wind vector and specific humidity) at 400 hPa level during the winter-spring season (February to April) between years with higher and lower Dasuopu accumulation rate (higher-lower). The filled rectangle indicates the Dasuopu core drilling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

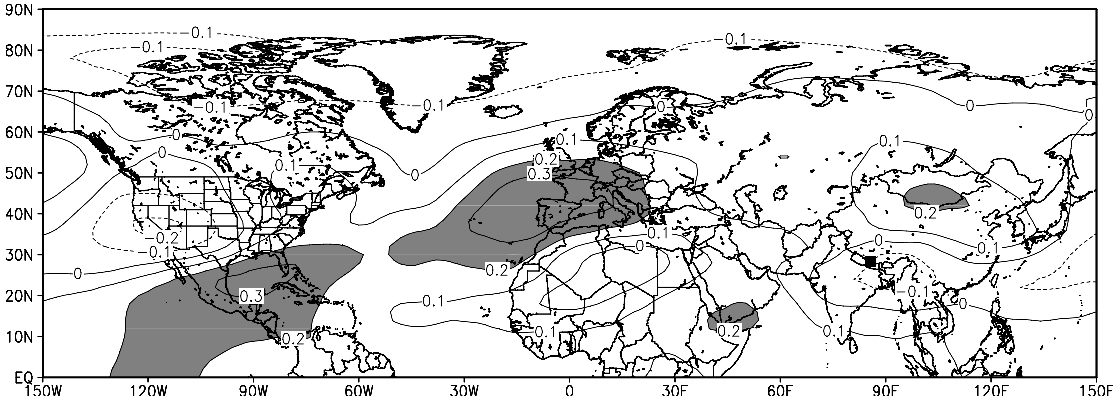

Figure 6. Correlation coefficients between the annual mean Dasuopu $\delta^{18}O$ and mean air temperature during the non-monsoon season (October to May) at 400 hPa level since 1871. The monthly air temperature data with 2.0º×2.0º resolution are from the twentieth century reanalysis (V2). Grey shadow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

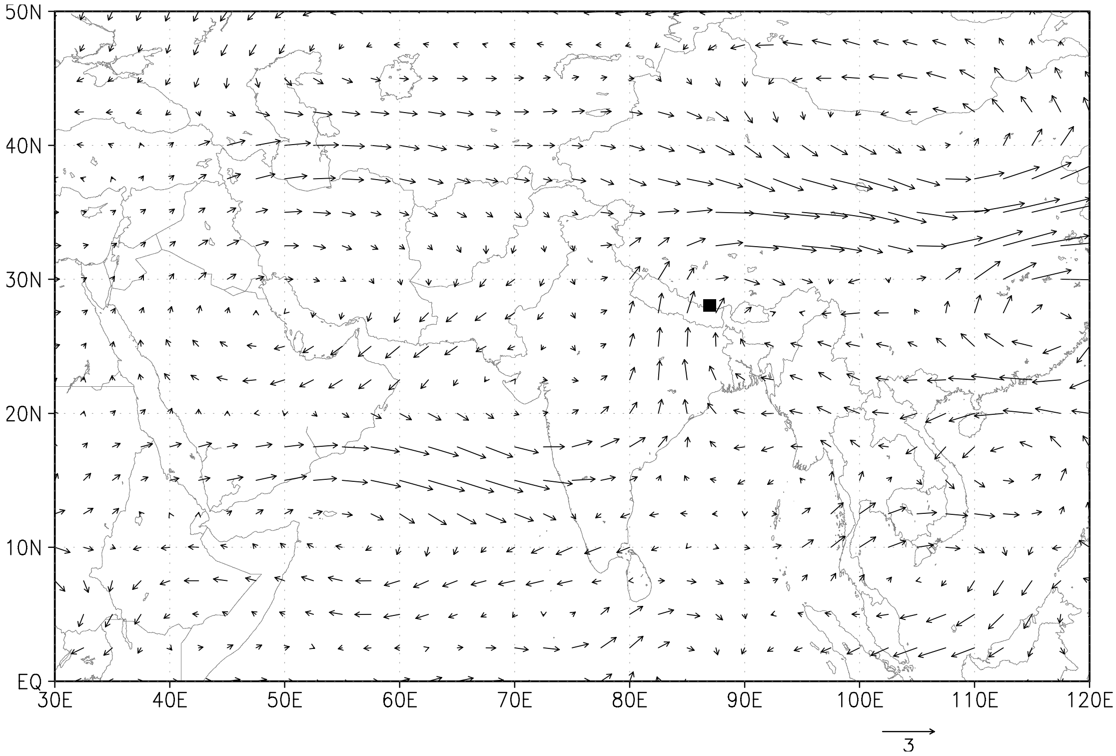

Figure 7. Composite analysis of summer mean (June to September) moisture flux (multiplying by wind vector and specific humidity) at 400 hPa level between years with higher and lower ER accumulation (higher minus lower). The filled rectangle indicates the ER core drilling site.

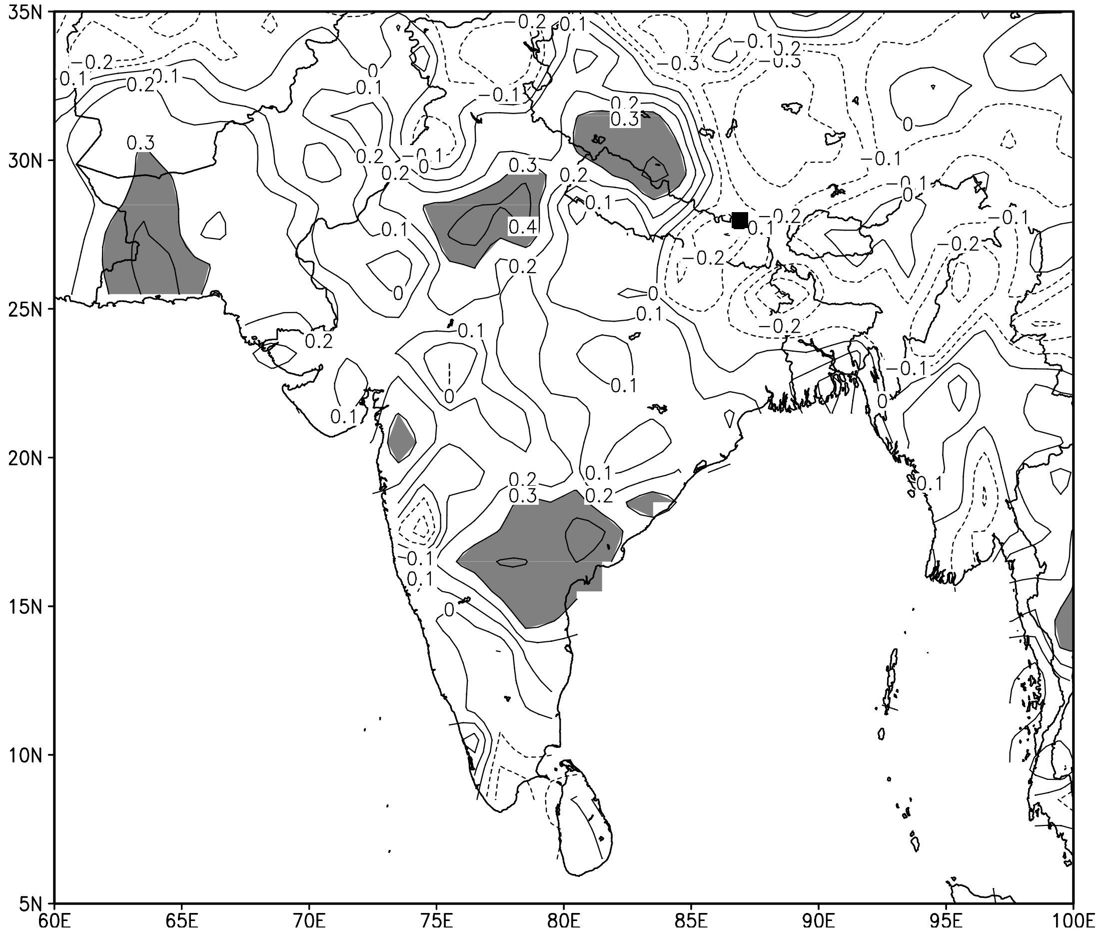

Figure 8. Correlation coefficients between the ER accumulation rate and summer (June to September) precipitation over the period 1951-2001. Grey shadow indicates correlation significance at 95% confidence level. The filled rectangle indicates the ER core drilling site. Summer precipitation data is from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

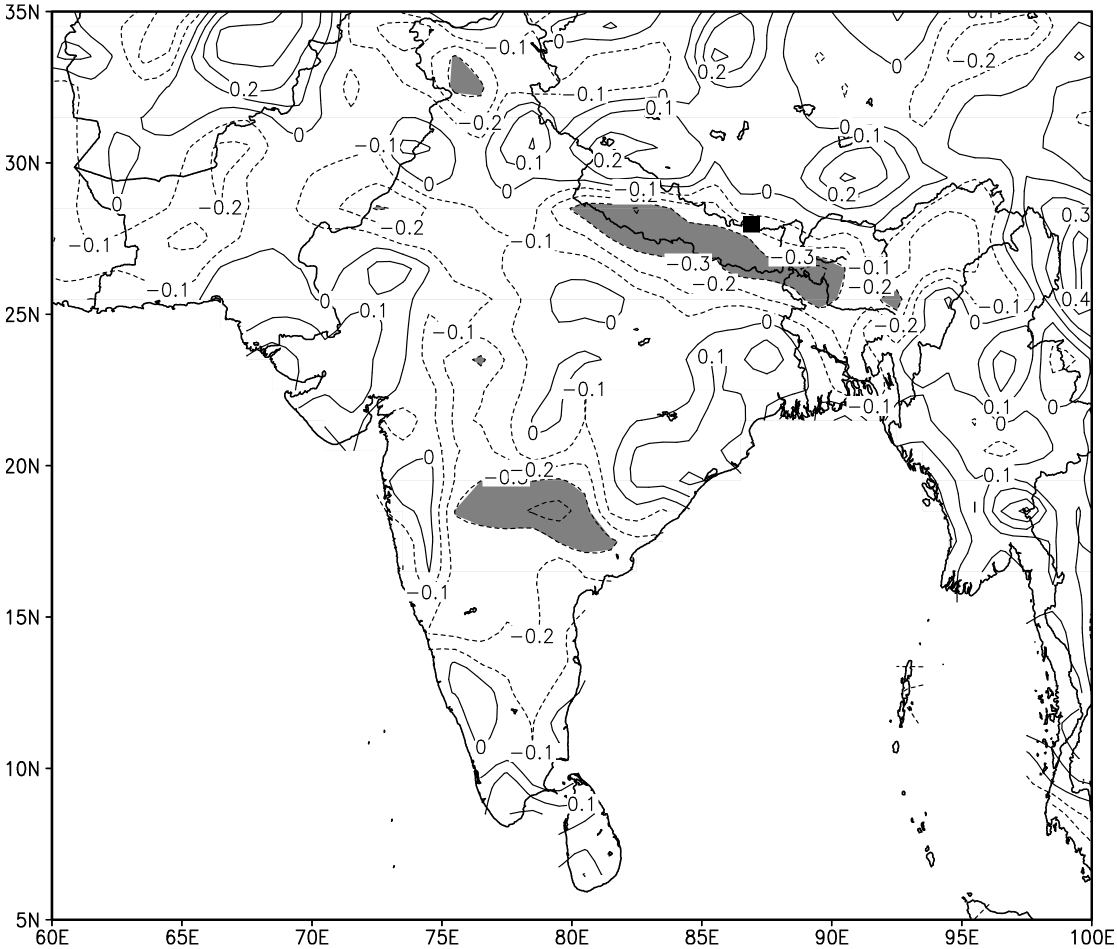

Fig. 9 Correlation coefficients between the ER $\delta^{18}O$ record and summer (June-September) precipitation over the period 1951-2001. Grey shadow indicates correlation significance at 95% confidence level. The filled rectangle indicates the ER core drilling site. Summer precipitation data is from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