Forcings of mass-balance variability in Karakoram-Himalaya

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Background

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Snowfall Variability Dictates Glacier Mass Balance Variability in Himalaya-Karakoram

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Glaciers in the Himalaya-Karakoram (HK) are critical for ensuring water-security of a large fraction of world's population that is vulnerable to climate impacts. However, the sensitivity of HK glaciers to changes in meteorological forcing remains largely unknown. We analyzed modelled interannual variability of mass balance (MB) that is validated against available observations, to quantify the sensitivity of MB to meteorological factors over the HK. Within the model, snowfall variability (0.06 m/yr) explains ~60% of the MB variability (0.28 m/yr), implying a sensitivity of MB on snowfall to the tune of several hundreds of percent. This stunningly high sensitivity of MB to snowfall offers crucial insights into the mechanism of the recent divergent glacier response over the HK. Our findings underscore the need for sustained measurements and model representations of the spatiotemporal variability of snowfall, one of the least-studied factors over the glacierized HK, for capturing the large-scale and yet region-specific glacier changes taking place over the HK.

The Himalaya-Karakoram (HK), covering a glacierized area of ~41,000 km^2 is one of the largest mountain ranges on Earth[1]. HK is surrounded by densely populated countries of south Asia and more than 800 million people depend strongly on water originating in its river systems (Indus, Ganges and Brahmaputra) for drinking, irrigation, hydropower, and industrial purposes[2,3]. Given the intrinsic variability of regional precipitation fed by Western Disturbances (WDs) and Indian Summer Monsoon (ISM), HK glaciers buffer a significant fraction of the population against droughts[3]. Climate change is threatening the future of glaciers in the HK[4], putting this dynamic water reserve under severe stress and causing serious hydrological changes[3,5,6]. This is likely to expose a significant fraction of regional population to serious climate impacts[3,7,8]. Understanding the details of the climatic forcing that is driving the glacier changes over the HK, therefore becomes an imperative for future adaptation and mitigation strategies.

The glaciers over Karakoram are mostly fed by snowfall occurring during winter months (November to April) derived from WDs while glaciers in the Himalaya receive snowfall from both WDs and ISM[9]. Region-wide remote-sensing glacier mass balance (MB) estimates have revealed that HK glaciers have mostly been experiencing a mass loss in recent decades[10,11]. Available field data from a handful of Himalayan glaciers also confirm this fact[12,13]. However, the pattern of the mass loss is quite heterogeneous; glaciers in the Himalaya are losing mass at rates that vary locally[11,12] while Karakoram glaciers have been in a near mass-balanced state over the past few decades[10,14,15]. The anomalous behavior, initially termed as "Karakoram Anomaly"[16,17], is now found to be centered in Kun Lun Shan[10]. The heterogeneous mass balance behavior over HK points to local idiosyncrasies of net climate forcing and glacier response that await a clear explanation.

Due to the harsh field conditions, only a few studies have been attempted to understand the meteorological forcing of glacier MB in the HK using *in-situ* data[18,19]. Relevant meteorological field-data from the glacierized high mountains of the region are quite limited[20,21]. A few model studies have investigated the regional glacier MB patterns utilizing various interpolated/reanalyzed meteorological data products[21–24]. A recent study[25] elucidated the importance of local MB sensitivity to temperature in determining glacier response. Another study using station data over the Karakoram and Tibetan Plateau suggested that cooling summertime surface air temperatures induce less glacier melting over the Karakoram. This cooling is further linked with the "Karakoram Vortex" under

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Introduction – Why are Glaciers Important?

- The Himalaya-Karakoram (HK), covering a glacierized area of ~41,000 km2 is one of the largest mountain ranges on Earth.
- HK is surrounded by densely populated countries of south Asia and people depend strongly on water originating in its river.
- The glaciers over Karakoram are mostly fed by snowfall occurring during winter months (Nov to April) derived from WDs while glaciers in the Himalaya receive snowfall from both WDs and ISM.
- Due to the harsh field conditions, limited studies have been attempted to understand the meteorological forcing of glacier MB in the HK using in-situ data.
- The primary objective of the present study is to identify the major meteorological drivers of mass-balance (MB) fluctuation over the HK region.

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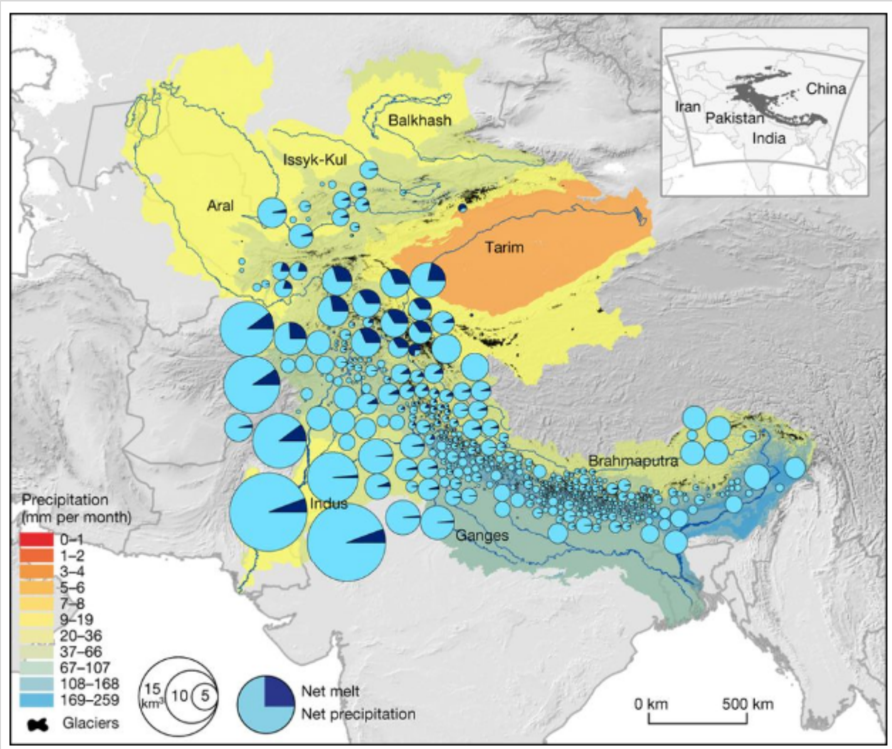
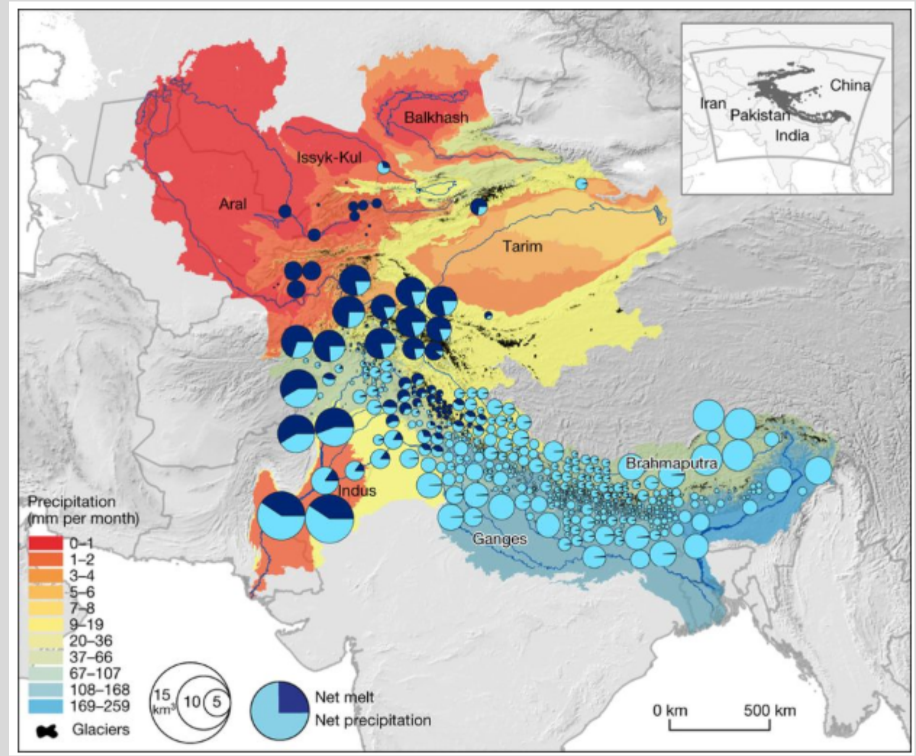
Glaciers act as buffer to drought





Precipitation and glacial melt inputs in an average year (*Left*).
Precipitation and glacial melt inputs in a drought year (*Right).*

(Pritchard, *Nature, 2017)*

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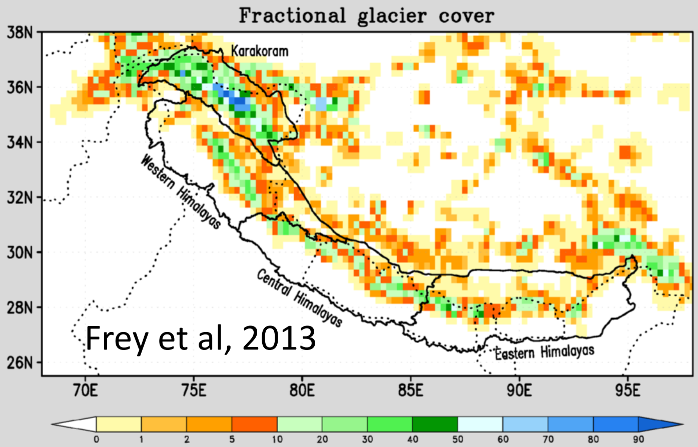
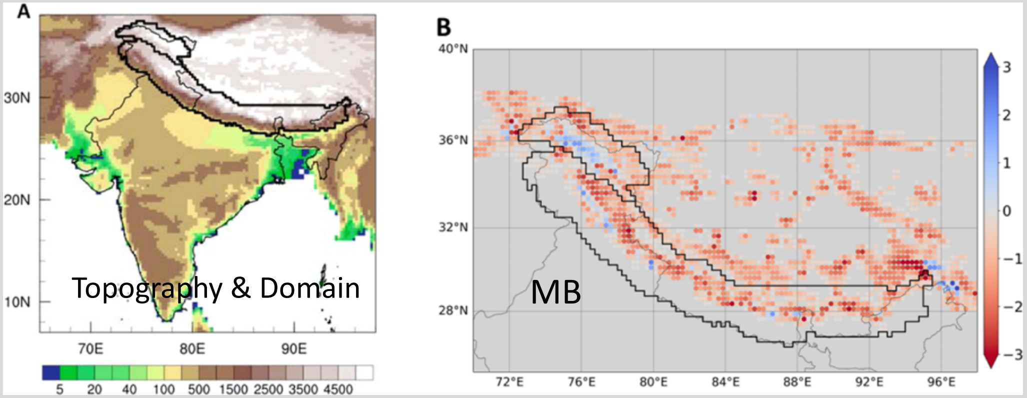
Study Region

- Due to the harsh field conditions, only a few studies have been attempted to understand the meteorological forcing of glacier MB in the HK using in-situ data.
- REgional MOdel (REMO) coupled with a dynamic glacier scheme ($REMO_{glacier}$) is capable of reproducing the general pattern of decadal-scale glacier mass changes in the High Mountain Asia, including the **Karakoram Anomaly !**
- In the present study, annual MBs over the HK region during 1989–2016 are simulated using $REMO_{glacier}$ for the glacierized fraction of each grid cell.





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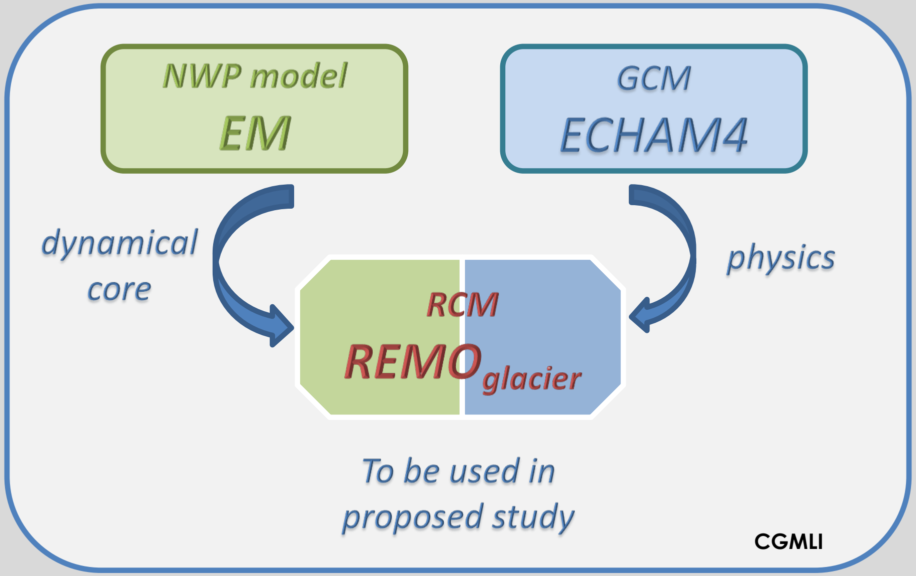
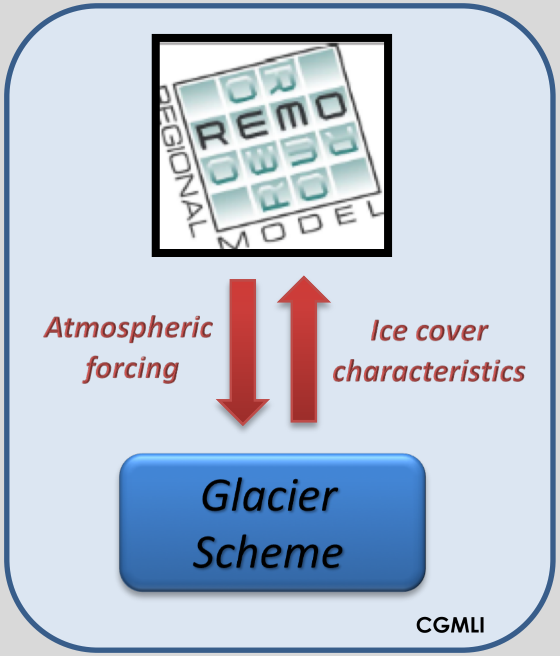
Methodology - $REMO_{glacier}$



Shows the dynamical core and physical parameterisations used in $REMO_{glacier}$



The general concept: Setup of a coupled modelling system.

Adapted from Kotlarski et al., 2010

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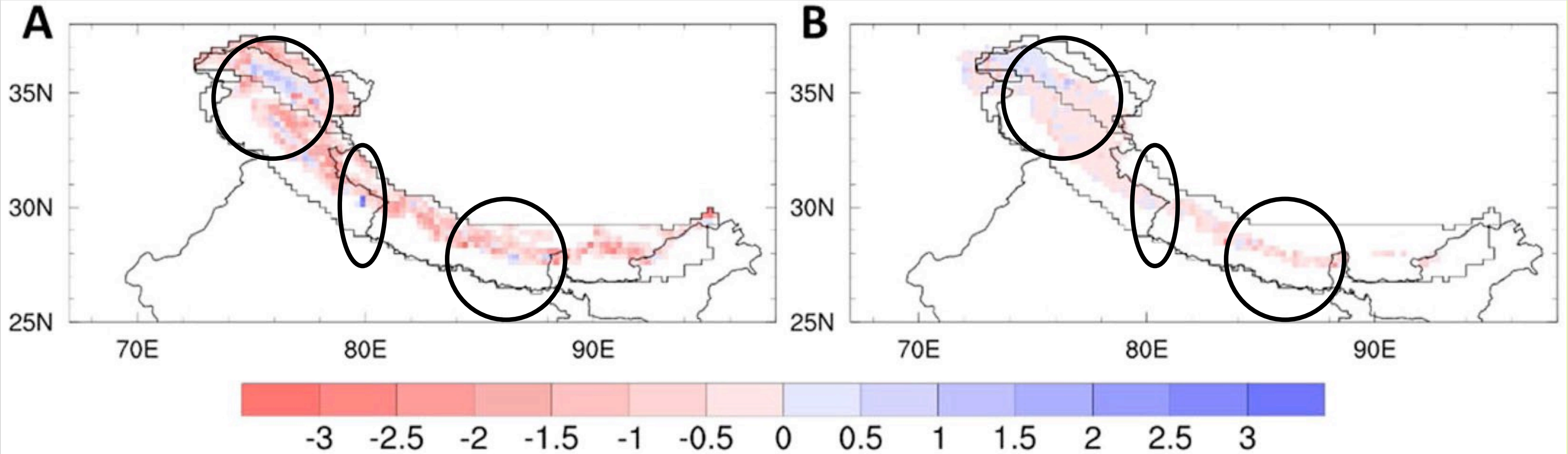
Results

Region-wide validation of modelled mass balances



Left, REMO$_{glacier}$ simulated mean MB (m.w.e./yr). Right Geodetic MB calculated (m.w.e./yr) for the period 2000–2016.

- reasonable match though model estimates are systematically more negative.
- despite the model limitations, the general consistency with observation

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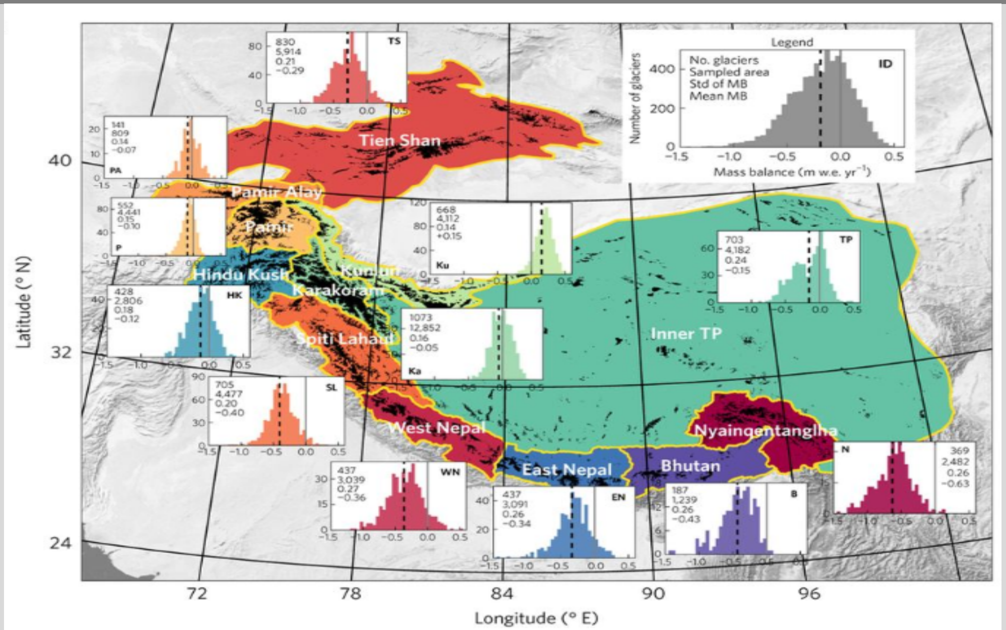
Mean Mass Balance over HK 2000-2016

Mass balance for High Mountain Asia (2000–2016). All the datasets are ASTER product. *(Source: F. Brun et al., 2017)*



MB	East Nepal	Hindu-kush	Nyain-qenta-nglha	Bhutan	Pamir	Kara-koram	Kunlun	Lahaul Spiti	West Nepal
FB	-0.33	-012	-0.62	-0.42	-0.08	-0.03	0.14	-0.37	-0.34
Model	-0.43	-0.76	-0.53	-1.33	-0.80	0.01	-0.48	-0.53	-0.96
Diff.	0.10	0.64	0.09	0.91	0.72	0.04	0.66	0.16	0.62

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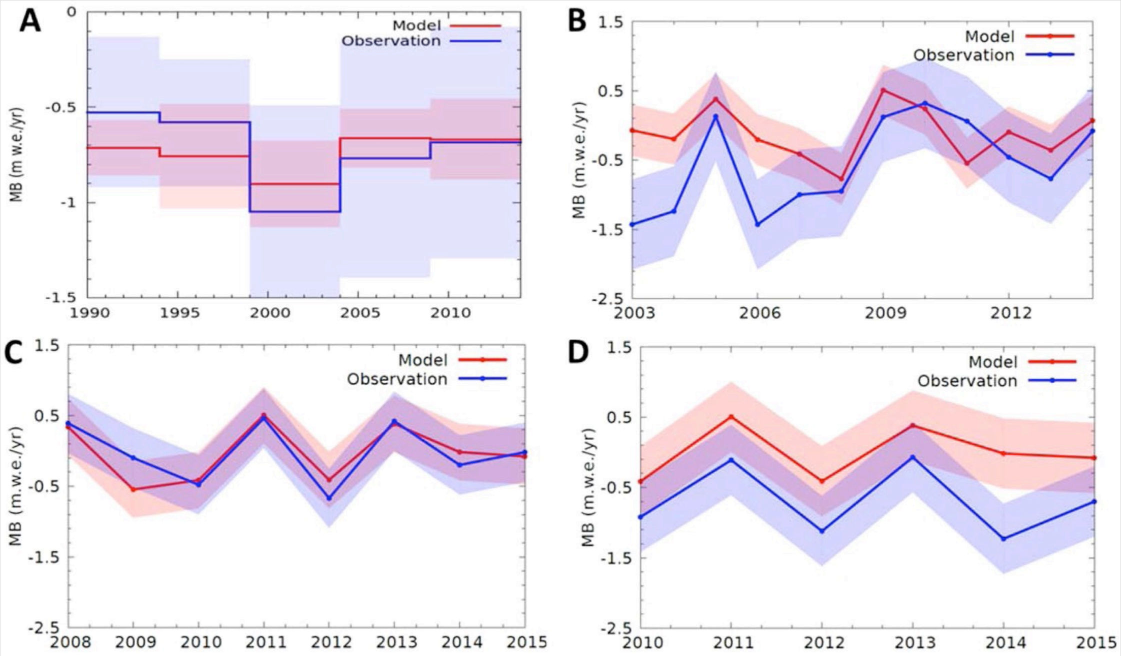
Glacier-wide validation of modelled MB



(A) *A comparison of pentadal averages of modelled annual MBs (red line) with that of pentadal averages from all the available field observations of MBs (blue line) from 24 glaciers over 1990–2014 period.*

(B) *A comparison of modelled annual MB (red line) with that of available field annual MBs (blue line) on Chhota Shigri Glacier over 2003–2014*

(C) *Mera Glacier for period 2008–2015*

(D) *Pokalde Glacier for 2010–2015.*

The model is reasonably good at capturing the individual glacier mass balances and interannual variability for the three glaciers namely, Chhota Shigri, Mera and Pokalde glaciers with significant correlations.

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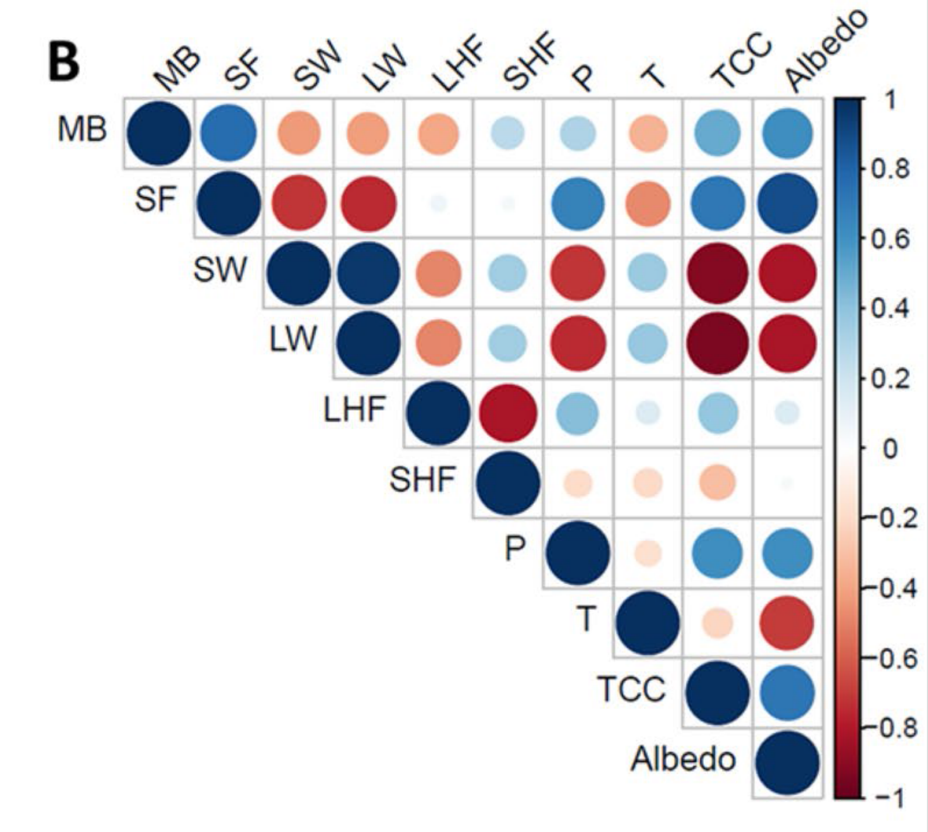
Fluctuations of modelled mass balance and its drivers

- The correlation matrix **(B)** reveals that SF variability has the strongest correlation with the MB response, with a correlation coefficient (CC) of 0.76 ($p < 0.001$) within our model assumptions.
- A strong MB sensitivity of ~470% to changes in SF exist in the HK.
- This is due to a strong effect of SF on net budget of SW (CC = −0.72, $p < 0.001$) through its control on albedo (CC = 0.88, $p < 0.001$) and association with TCC (CC = 0.71, $p < 0.001$)



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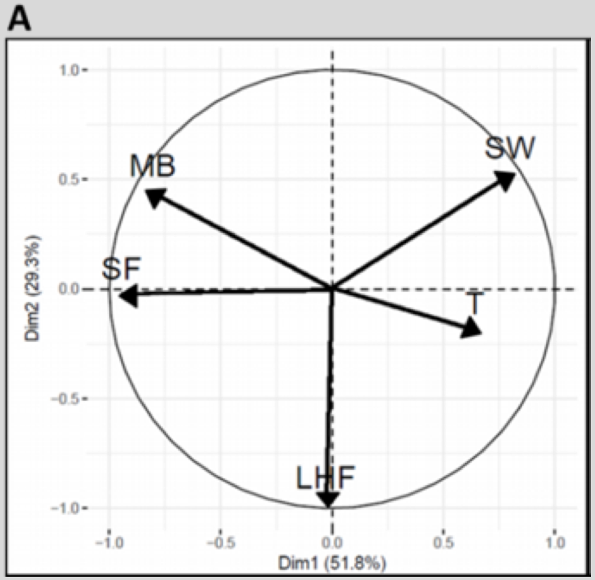
Model Parameters Correlations

- The surprisingly dominant role of SF in controlling MB is also verified with a principal-component analysis (PCA) of the correlation matrix.
- We only consider the variables MB, SF, SW, T, and LHF. We exclude LW and SHF due to their strong correlations with SW and SHF respectively. Similarly, albedo and TCC have strong correlations with SF and, therefore, are neglected.



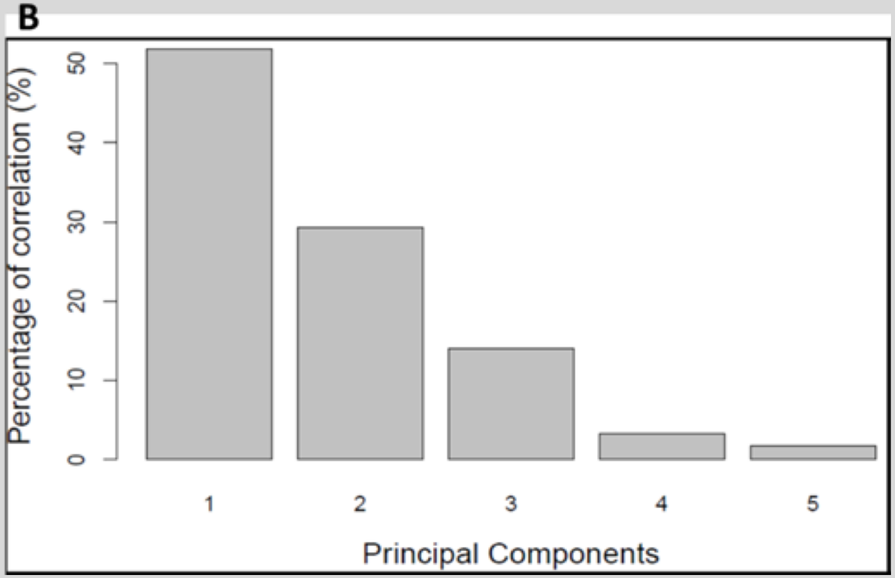


Figure: Principal Component Analysis (PCA). A) Biplot is showing the result of a PCA of the correlation matrix of the interannual variability of MB, SF, SW, T, and LHF. **B)** A screeplot showing the percentage of correlation accounted for by the principal components.

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MB and Snowfall relationship

- The cooperation among the factors amplifies the net effect of SF variability on MB, resulting in a very large sensitivity of MB to changes in SF.
- Therefore individually MB and SF interannual variability is discussed over different regions e.g., HK, Himalaya and Karakoram.
- This critical role of the SF variability as a MB driver is, in fact, evident from a simple and yet striking plot in the time-series analysis.
- The figure given below shows that the role of SF is stronger in the Karakoram than in the Himalaya.

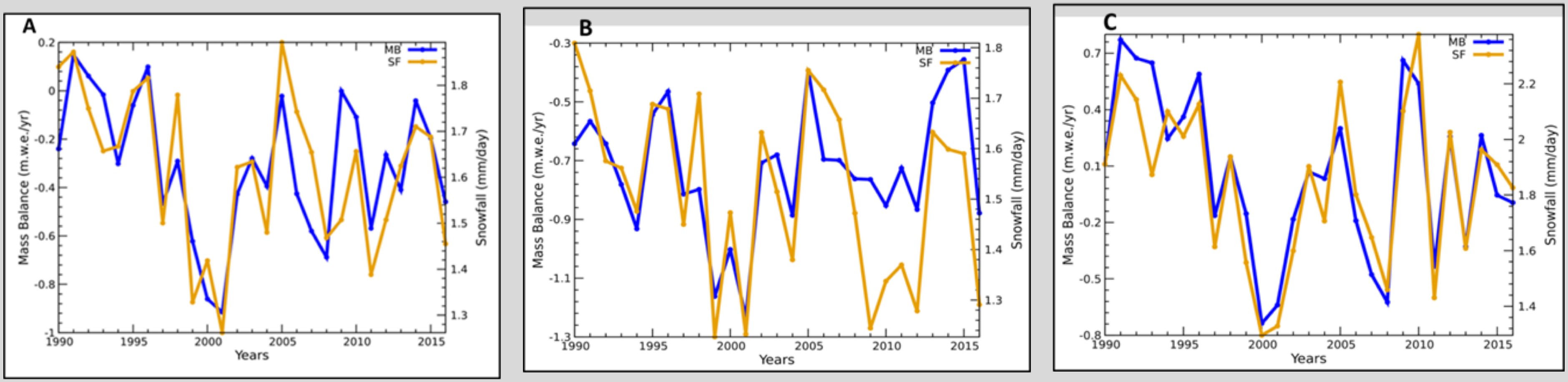

Figure: Interannual variability of SF and MB in the HK (left), Himalaya (middle) and Karakoram (right) for the period 1990-2016

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Conclusion

- The simulated MB show an overall negative MB but also reveal regions with positive MB anomalies especially over the Karakoram.
- For the whole HK region, it has been found that MB simulated by model is able to capture observational variability reasonably well.
- The annual glacier MB variability in the HK over the last two and half decades is essentially driven by the variability of mean annual snowfall.
- A relative insensitivity of snowfall to the local temperature changes are responsible for the Karakoram anomaly.
- It is thus apparent that understanding the recent and future climate forcing and the corresponding response of the HK glaciers require a strong handle on snowfall variability and its trend.

Thank you for reading it!

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