REMO$_{glacier}$ Model and its Application in Karakoram Himalayas

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Abstract: ***The ongoing environmental changes driven by anthropogenic activities are affecting all parts of the Earth, including the cryosphere. Unlike polar regions, quantifying changes in mountain glaciers is challenging due to physical and technical constraints and a lack of historical data. Modeling these changes is a viable solution, and REMOglacier is a step in that direction. By implementing a glacier parameterization scheme into the regional climate model REMO, it is possible to simulate mass balance and changes in the areal extent of glaciers on a subgrid scale. This paper reviews studies using the REMOglacier model to analyze glacier changes in the Karakoram Himalayas. Results indicate that simulated mass balances align with observations, capturing the Karakoram Anomaly. REMOglacier has proven effective in simulating glacier mass balance changes and can significantly aid in formulating climate actions to protect these sensitive zones.***

Keywords: Glaciers, Regional Climate Modeling, Reanalysis Datasets, Glacier Mass Balance, Surface Energy Balance, Sub - grid Parameterization, Volume Area Relation, Equilibrium Line Altitude

1. Introduction

Glaciers are vital indicators of climate change due to their sensitivity to climatic conditions, resulting in melting, retreat, and sometimes complete disappearance (IPCC, 2007). Quantifying these changes is challenging, particularly for mountain glaciers, due to high altitudes, difficult terrain, and a lack of historical data. However, quantification is crucial as glaciers influence climate via feedback mechanisms, impacting surface energy balance and serving as significant freshwater sources (IPCC, 2007; Kotlarski et al., 2010)).

But why is the quantification of these changes so important? This is because glaciers are known to influence the climate via feedback mechanisms. Changes in the form, thickness, temperature, and albedo of ice and snow, all impact the climate directly or indirectly. Usually with their high albedo and very low temperatures (below 1^0C), they cause the cooling of overlaying air mass and further modifications in small - scale circulations, thus changing the surface energy balance. (Kotlarski et al., 2010) Glaciers are also the single most important sources of fresh water on the Earth besides the groundwater aquifers. Also, glacial melt causes the sea - level rise. (IPCC, 2007) Hence, changes in the climate have the potential to accelerate or decelerate various glacial phenomena which in turn will undeniably impact every person on the planet.

The Himalayas, home to the largest concentration of glaciers outside the poles, are critical for nearly 2 billion people downstream, earning the moniker "Water Tower of Asia. " Additionally, with the geopolitics of South Asia, with India, Pakistan, and China, all having strained relations and some Himalayan regions under their control, the importance of the Himalayas only gets enhanced. But, it's not untouched by global climate changes. The majority of glaciers in the region have shown significant retreat over the years, including the famous Gangotri glacier (Naithani et al., 2001). While most Himalayan glaciers are retreating, the Karakoram glaciers exhibit stable to positive mass balance, known as the Karakoram Anomaly (Javed et. al, 2022, Dimri, 2021, Farinotti et. al, 2020, Dasgupta et. al, 2022). Quantifying changes in these glaciers is especially difficult due to their high altitudes, hostile terrain, and lack of monitoring stations (Kumar et al., 2019).

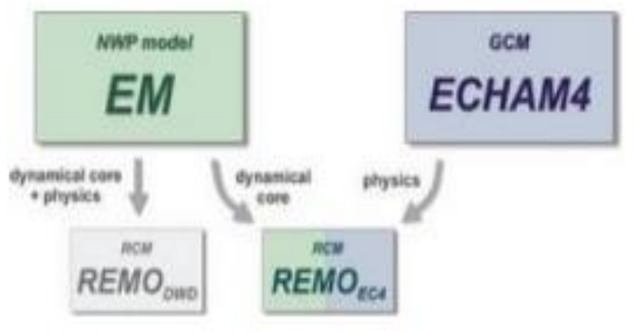
Owing to all these difficulties, simulated observations using environmental modeling seem to be the way. But it's always easier said than done. Traditional general climate models (GCMs) and regional climate models (RCMs) use static glacier masks that define a land point as either being glacierized or not glacierized at all. Moreover, they are unable to simulate any changes in the glacier ice or glacier volume. Also, glaciers situated outside of poles are smaller than the resolved scale of climate models, causing further complications. (Kotlarski et al., 2010) Hence, glaciers and ice caps outside of the poles cannot be simulated using these traditional models. To overcome all these challenges, what was required was an interactive glacier energy and mass balance scheme that includes the dynamic adjustment of glacierized area. This was achieved with the development and implementation of the glacier parameterization scheme with REgional MOdel (REMO), leading to the development of REMO$_{glacier.}$ (Kotlarski et al., 2010)

Modeling using REMOglacier, which integrates a glacier parameterization scheme into the REMO regional climate model, overcomes these challenges. This paper discusses the model's specifications, and its application in the Karakoram, and compares its results with available datasets.

2. Models and Methods

1) The regional climate model - REMO

A limited area three - dimensional hydrostatic atmospheric circulation model called REMO was used as the basic modeling tool for the development of glacier parameterization. (Jacob et al., 2001) Its dynamical core is based on the former numerical weather prediction (NWP) model of the German weather service (Europa - Modell, Majewski, 1991). Its physical parameterizations were adopted from GCM ECHAM 4 and 5 (Roeckner, 1996).



Dia1: Development of RCM REMO (Source: *REMO page*)

At the lateral boundaries of the regional model domain, REMO's prognostic atmospheric variables are loosened to a large - scale forcing provided by GCM or by reanalysis product. At the lower boundary, the REMO is forced by the respective land and sea surface features to which the so - called tile approach is applied: the total area of an individual model grid box that may include a portion of land, water, and sea ice at a sub - grid scale (tiles, expressed as a percentage). Surface fluxes for each tile are calculated separately and then averaged within the lowest atmospheric level using the respective area contributions as weights. In the standard REMO setup, glaciers and ice caps are represented by time - constant static glacier masks. Therefore, only polar glaciers and ice caps are shown in these models in the name of the cryosphere (Kotlarski et al., 2010).

2) Glacier Sub - grid Parameterization

Changes in the existing setup of RCM REMO were undertaken to account for the energy and mass balance changes in the mountain glaciers, which were mainly concerned with physical parameterizations (Kotlarski et al., 2010). The resultant model was thus called $REMO_{glacier}$. Currently, available RCM resolutions of 10 - 50km are too coarse to resolve individual mountain glaciers, hence the mean behavior of all the glaciers contained in an RCM grid box has to be described on the sub - grid scale. Besides, spatially resolved simulation of individual glaciers is not only cumbersome but also increases the computing time. The basic characteristics of the parameterization scheme are as described in the following sections (all based on the original work by Kotlarski et al., 2010).

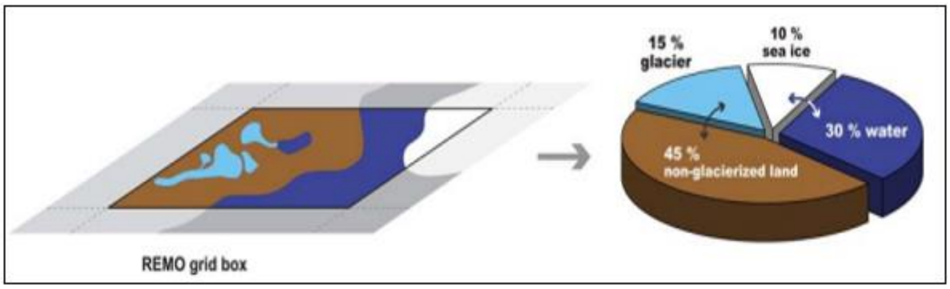
a) Fractional Surface Coverage and Cuboid concept

A fourth subgrid tile - glacier, was introduced in the model to account for mountain glaciers on the subgrid - scale. It represents the total area covered by glaciers in the respective grid cell. Additionally, this glacier tile is allowed to grow or shrink depending on mass balance but is restricted to the total land surface area of a grid box.

Simplification

A major simplification in the model involves the pooling of all individual glaciers located in a specific grid box into one single ice body in the form of a 2 - layered cuboid with a surface area 'A' and a total thickness of 'h'. Resultant volume 'V' would indicate the sum of estimated volumes of all the individual glaciers. This pooling of glaciers is supported by previous observations that nearby glaciers often show a similar response to a given climatic forcing in terms of their mass balance evolution.

Besides some other minor simplifications including -
- Glacier cuboids of adjacent grid boxes are assumed to be non - interacting and independent of each other.
- Large - scale ice flows across grid boxes are also neglected.
- The altitude of the glacier cuboid surface is assumed to be identical to the mean grid box altitude, and consequently the effect of surface elevation mass - balance feedback is not taken into account.
- A constant ice density is assumed for glaciers in the entire cuboid.



Dia 2: The extended tile approach. Example for a grid box covered by non - glacierized land (45%), glacier (15%), water (30%), and sea ice (10%). (Source: Kotlarski et al., 2010)

b) Surface energy balance, Mass balance, and Glacier Area Calculation

At each time step, the total equilibrium energy of the surface glacial fraction is calculated by: $dQ_{ice/snow}$= K+L+H+LE+G+M; where, K=short wave radiation, L=long wave radiation, H=surface heat flux; LE=latent heat flux; G=ground heat flux; the amount of energy consumed by melting ice and snow; $dQ_{ice/snow=}$ energy change of heat content upper snow or ice layer.

The modeled mass balance (MB) of the cuboid is assumed to represent the mean specific mass balance. In general, the mass balance is the difference between the accumulation and ablation in a glacier. Main accumulation processes include mostly snowfall and rime formation. Snowfall rates were determined by the atmospheric model component which also included the possible modifications due to subgrid redistribution of snow accumulation. As for ablation, the transformation of snow into ice is parameterized via a snow age threshold of 730 days. If the temperature threshold of

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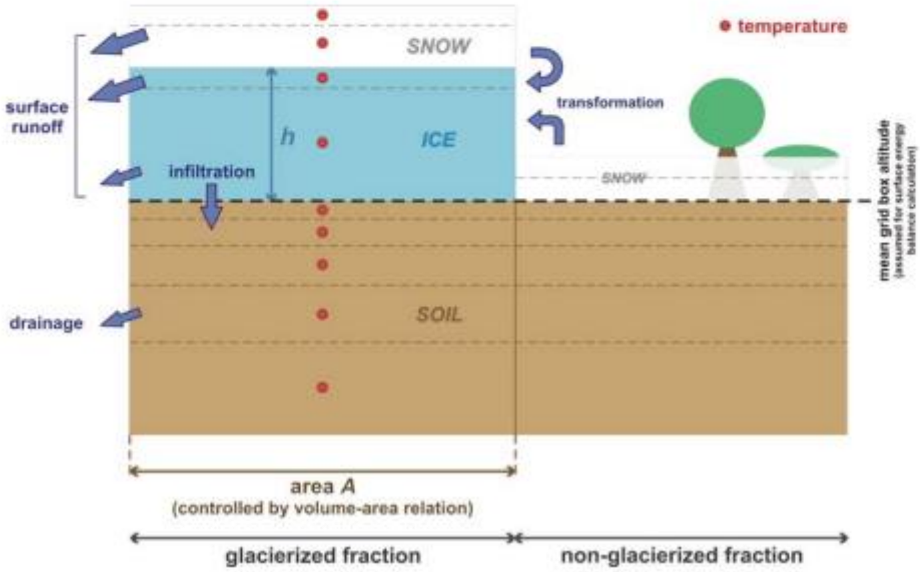
0°C is exceeded due to positive surface energy balance or heat diffusion, then the temperature is adjusted back to 0°C and the released energy gives the ice/snow melt in the respective layer. Mass balance (MB) can be calculated as MB= SF – (K+L+H+LE) / ρLH + ε; where ρ= density of ice, LH is the latent heat of melting, and ε denotes relatively minor contributions to this balance.

Assuming steady - state conditions, glacier area thickness is related to the volume by a general power law: $V= cA^{\lambda}$; where c and λ are empirical constants. Previous studies have established that mean glacier thickness increases with glacier area and therefore glacial volume can be obtained from glacier area data.

Simplifications
- The aging effect is not considered.
- A snow age threshold of 730 days is known to vary in different areas.
- Snow cover thickness is assumed to be constant over the entire glacial cuboid.
- Glacial cuboid is assumed to be either completely snow - covered or completely ice - free.
- Another major simplification is that mass balance changes are assumed to be uniform over the entire glacial cuboid.



Dia 3: Profile through the land fraction of a partly glacierized grid box in REMOglacier. (Source: Kotlarski et al., 2010)

c) Accounting for Atmospheric Sub - grid Variability

In an RCM subgrid, there'd be obvious differences in climate forcings in glacierized and non - glacierized fractions, such as chilly moist conditions in glacierized fractions, shading effect, and effect of inclination of slopes, which all in turn impact global radiation flux and atmospheric circulations. To include these effects, subgrid variability of snowfall and global radiation was accounted for using simple scaling concepts. In each time step, both quantities are redistributed in an RCM grid tile between the glacierized and the glacier - free surface fraction based on current glacier outlines in the study region utilizing a high - resolution observational precipitation dataset and the application of an offline radiation model, that accounts for sloping and shading effects.

d) Glacier Inventory

It was prepared to cover the glacierized portion of the RCM subgrid. It comprises all the mountain ranges in the region. Glacier data had been obtained from the Global Land Ice Measurements from Space database [GLIMS], glacier data published by the International Centre for Integrated Mountain Development [2007], and the Environmental Systems Research Institute's Digital Chart of the World. Because of differences in sources, there are differences in data quality, acquisition dates, and glacier parameters. Glacier areas were derived using glacier polygons, while topographic parameters were derived from a void - filled version of Shuttle Radar Topography Mission DEM (2007).

e) Experimental Design

$REMO_{glacier}$ was integrated over entire South Asia for a period beginning from 1989 to 2016 for a horizontal resolution of $0.22^{O} * 0.22^{O}$ (~25km) with 27 vertical levels, with lateral boundaries driven by the ERA Interim (ERA I) dataset. Then, using glacier inventory glacierized grid box fraction was initialized at the very first time step. . The lateral boundaries have a temporal resolution of 6 hours and are interpolated into a two - minute time step (Kumar et al., 2015, Kumar et al., 2019).

3) Comparison datasets used

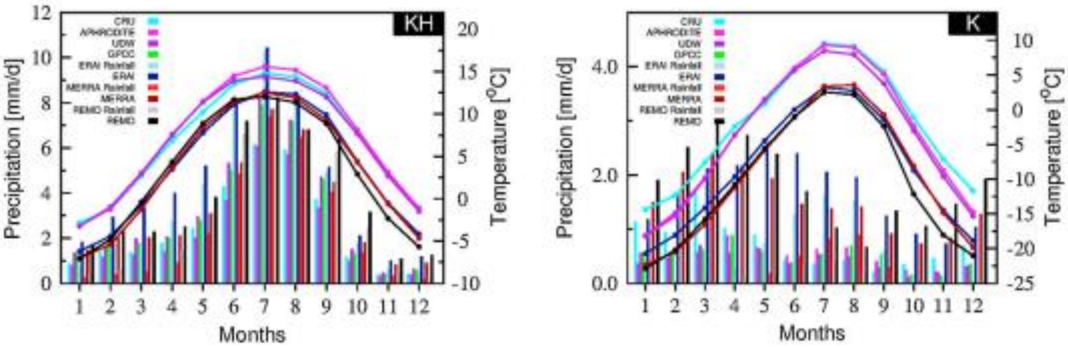
Due to the general lack of observational data in the KH region, the validity of the simulated patterns had to be validated with the observational data from nearby Himalayan glaciers like Chota Shigri (2003 - 2014), Pokalde (2010 - 2015) and Mera (2008 - 2015) (Kumar et al., 2015). The observation data for temperature and precipitation were obtained from CRU V3.1, UDW, Aphrodite, and GPCC. Besides, snowfall variability was validated with the observations of 4 IMD weather stations situated in the Western Himalayas step (Kumar et al., 2015, Kumar et al., 2019). Apart from these observational datasets, the efficiency of the model was also tested against reanalysis datasets from ERA - Interim, ERA5, and MERRA.

3. Results

1) Precipitation and temperature

It was found that the simulated results captured very well the annual cycles of temperature and precipitation in the region. Even the spatial heterogeneity in precipitation that takes place due to altitude, topography, and orographic lifts are all captured well. This makes this model simulation more effective than reanalysis datasets like ERA I and MERRA which are unable to capture these variations because of their coarser resolutions and faulty orographic change estimations. (Kumar et al., 2015, Kumar et al., 2019)

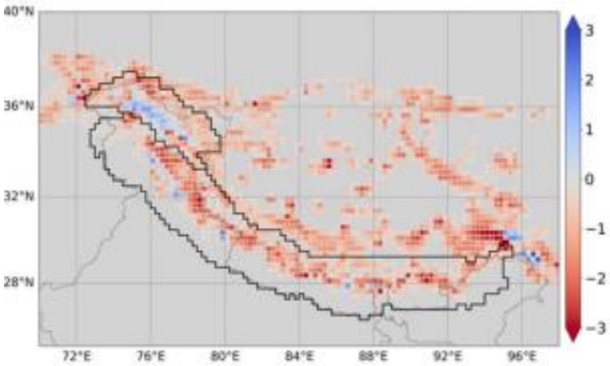
As for precipitation, the simulated estimations although largely agreeing with reanalysis datasets, show overestimation concerning observations. However, the model reproduces the trend of KR receiving most of its precipitation during winters in the form of snowfall. However, the estimations of annual mean precipitation were found to be 20% more than MERRA and 150% - 300% more than observations. (Kumar et al., 2019) However, keeping in mind the limitations of reanalysis datasets and lack of actual observations from KR, besides the previous applicability of the model in other areas where there is the presence of enough observational records; it can be argued that modeled simulations might be more valid than observations.



Dia 4: Mean annual cycle (1989–2007) of precipitation (bars) and temperature (lines) over the entire K - H region (left) and the Karakoram (right). MERRA/ERAI/REMOglacier simulated precipitation is analyzed for both total precipitation (MERRA/ERAI/REMO) and rainfall (MERRA Rainfall/ERAI Rainfall/REMO Rainfall) (no snow). (Source: Kumar et al., 2015)

As for temperature, annual cycles are well captured. However, concerning observations, a negative temperature bias of almost 1^{O}C was seen. (Kumar et al., 2019) This consequently has resulted in the overestimation of solid precipitation in KR. However, simulated results are in line with the overall positive temperature trends as recorded via observations and MERRA datasets.

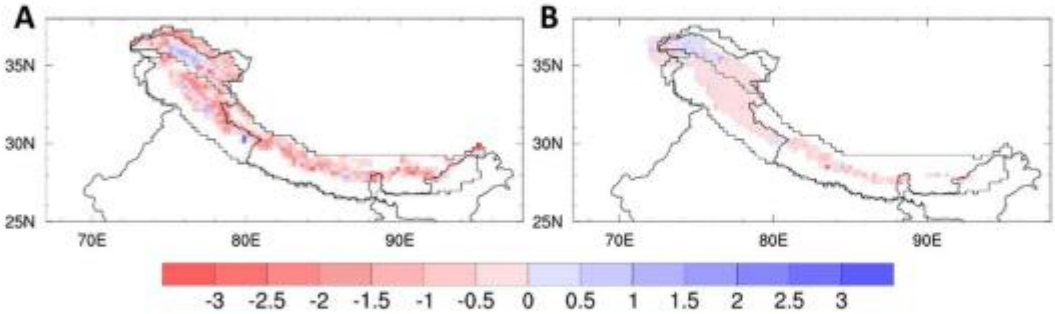
2) Mass balance studies and Equilibrium Line Altitude (ELA)



Dia 5: The modelled MB (m. w. e. /yr) pattern over the simulated domain, for the period 1989–2016. (Source: Kumar et al., 2019)

The simulated MB is the representation OF the mean specific MB averaged over all individual glaciers in the given model grid box. While all the other regions would display a negative mass balance (~ - 0.74 m. w. e. /yr), Karakoram (~+0.06 m. w. e. /yr) and Kunlun Shan mountains show a positive glacier balance. (Kumar et al., 2019) This is by the reports of positive mass balance in these areas. However, it is also known that without a topography filter, $REMO_{glacier}$ would give an overestimation of orographic precipitation (: Kotlarski et al., 2010), and consequently a positive mass balance bias was observed.

Modelled MB was compared with remotely sensed geodetic MB estimates across KH (2000 - 2016) (Kumar et al., 2019). A reasonable match between the two datasets was seen, although model estimates were found to be more negative. The difference between the two increased inversely to the extent of glacial fraction in a grid box. However, a model with its overall reproducibility of observations can be relied on for regional scale MB calculations.



Dia 6: Comparison of REMOglacier with geodetic data (A) REMO glacier simulated mean MB (m. w. e. /yr) comparison with (B) Geodetic MB calculated (m. w. e. /yr) for the period 2000–2016 (Source: Kumar et al., 2019)

Since no data was available for KR glaciers, validation of simulated MBs was done by comparing it with pentadal averages of all the available glaciological measurements of a few Himalayan glaciers, capturing the pentadal averages reasonably well. However as seen by comparisons with observations of individual glaciers such as Chota Shigri, Mera and Pokalde shows that due to its coarser resolution and simplifications in a grid box, it cannot measure changes accurately for individual glaciers.

Table 1: Validation of modeled mass balances with available mass balances (m. w. e. /yr) for Himalaya, Karakoram, and Chhota Shigri (CSG), Mera, and Pokalde Glaciers over different periods. *Pentad observation is the mean of 24 glaciers where some glaciological MB data is available (Souce: Kumar et al., 2019)

Regions	Measurement	Period (yr)	Modelled (m.w.e./yr)	Observed (m.w.e./yr)
Himalaya	Geodetic	2000–2016	−0.72 ± 0.05	−0.39 ± 0.02
Karakoram	Geodetic	2000–2016	−0.09 ± 0.09	−0.05 ± 0.03
HK	Geodetic	2000–2016	−0.39 ± 0.06	−0.28 ± 0.03
CSG	Field	2003–2014	−0.12 ± 0.10	−0.56 ± 0.18
Mera	Field	2008–2015	−0.03 ± 0.14	−0.02 ± 0.15
Pokalde	Field	2010–2015	−0.006 ± 0.15	−0.69 ± 0.20
Himalaya (pentad*)	Field	1990–2014	−0.76 ± 0.05	−0.72 ± 0.09

Equilibrium Line Altitude - The equilibrium line is an imaginary line that marks the region where the glacial mass balance is zero, i. e., the region that separates the accumulation and ablation zones within a period. That height is called the equilibrium line altitude (ELA). Across K - H, ELA estimates based on observations range from 4400 m to 5700 m. Karakorum's ELA estimate from REMO Glacier is 4949 m (Kumar et al., 2015), which is very close to the earlier reported estimates. However, some underestimation is seen. This indicates that the average mass balance of the simulated regions is larger than the true mass balance.

3) Fluctuations in drivers of MB changes

Analysis of simulated mass balances and their associated meteorological parameters over KH reveal that (Kumar et al., 2019)-

- Short wave radiations have the highest inter - annual variability followed by mass balance, long wave radiations, latent heat flux, surface heat flux, and others.
- Snowfall variability was seen to have the lowest variability during the simulated period.

However, it was found that variability in one factor was usually canceled out by variability in other factors and due to this, the strong correlation among the drivers was inferred. Resultantly, the correlation between all the drivers was analyzed, and snowfall variability was obtained to have the strongest impact on mass balance changes (Kumar et al., 2019). This is so because besides directly causing the accumulation, snowfall variability also influences the radiation budget by impacting the albedo and total cloud cover (TCC). Consequently, MB sensitivity is so strong in KR that for a snowfall variability of 0.06 m. w. e. /yr, the MB variability is 0.28 m. w. e. /yr, a strong sensitivity of nearly 470% (Kumar et al., 2019).

It was also observed that despite having nearly the same mean temperature changes in KH and the Himalayas, mass balance is nearly insensitive to these changes in KH, unlike the Himalayas. This has been attributed to the summertime cooling in KR because of the Karakoram vortex and the majority of its precipitation taking place in winters causing 90% of the precipitation to be solid. Hence, snowfall variability turns out to be the major factor driving the anomalous behavior of KR glaciers (Kumar et al., 2019).

4. Conclusion

The cryosphere of the earth with its snow and ice cover and extremely low temperatures are important areas that are known to store the major amount of Earth's freshwater in frozen form, influencing the various climate forces while also being very susceptible to changes in the climate forcing mechanisms. The majority of Earth's cryosphere is located in the polar areas, but even in some non - polar areas, the cryosphere exists in the form of mountain glaciers. The ever - increasing climate change and global warming phenomena have impacted these regions, the changes which are pretty easy to observe but very hard to quantify.

So, we take the help of modeling techniques, which due to their resolving limits can capture changes in polar areas owing to their large spatial extent. But the same cannot be said about mountain glaciers, which cover much smaller areas, are situated on high mountains, and have variable snow and ice cover changes throughout the year. Complexities increase in areas such as The Karakoram, where we have a complete lack of any observational records. So a glacier parameterization scheme was developed and implemented into the existing regional climate model REMO.

The results show that the observed regional mass balance and glacier extent changes are largely reproducible based on idealized concepts of glacier - climate interactions. They can realistically reproduce the annual cycles of various climatic phenomena and their general trends over the years. However, they do show uncertainties and differences in estimations. These limitations arise due to the inherent properties of the model which mainly include coarser resolutions, pooling of different glaciers into ne, over - simplification of various processes, neglect of inter - grid ice –flow, and improper accounting of sub - grid variability. In areas like Karakoram, the general lack of observational data further complicates the problem. But presently, among all the tools that we have, this modeling technique is one of the most efficient ways to determine the changes in the glacier mass balance and glacier area.

Future research should work on developing a modeling technique that cannot only capture the changes on a sub - grid scale but also the changes taking place in individual glaciers. Modeling techniques that give better estimations without much bias are desired for future research. Also, there is a need to set up more and more weather stations in these areas and carry out on - field experiments so that the simulated results of the modeling techniques can be verified with better comparison datasets. In that respect, even reanalysis datasets need to be tuned to finer fine resolutions and account for elevational and orographic changes.

However, despite all the limitations and uncertainties, $REMO_{glacier}$ has turned out to be an effective tool in simulating changes taking place in glaciers located in remote mountains. It has been found that not only can they tell about general trends, but they are even able to capture regional variability such as the Karakoram Anomaly. In the light of the changing global scenario, and predictions of significant melting in the upcoming future, it's to be seen if modeling techniques like these could be of any help.

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