Glaciers of Himalayas

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Uncertain economic consequences

- Water
- Food
- Energy
- Livelihoods & Jobs

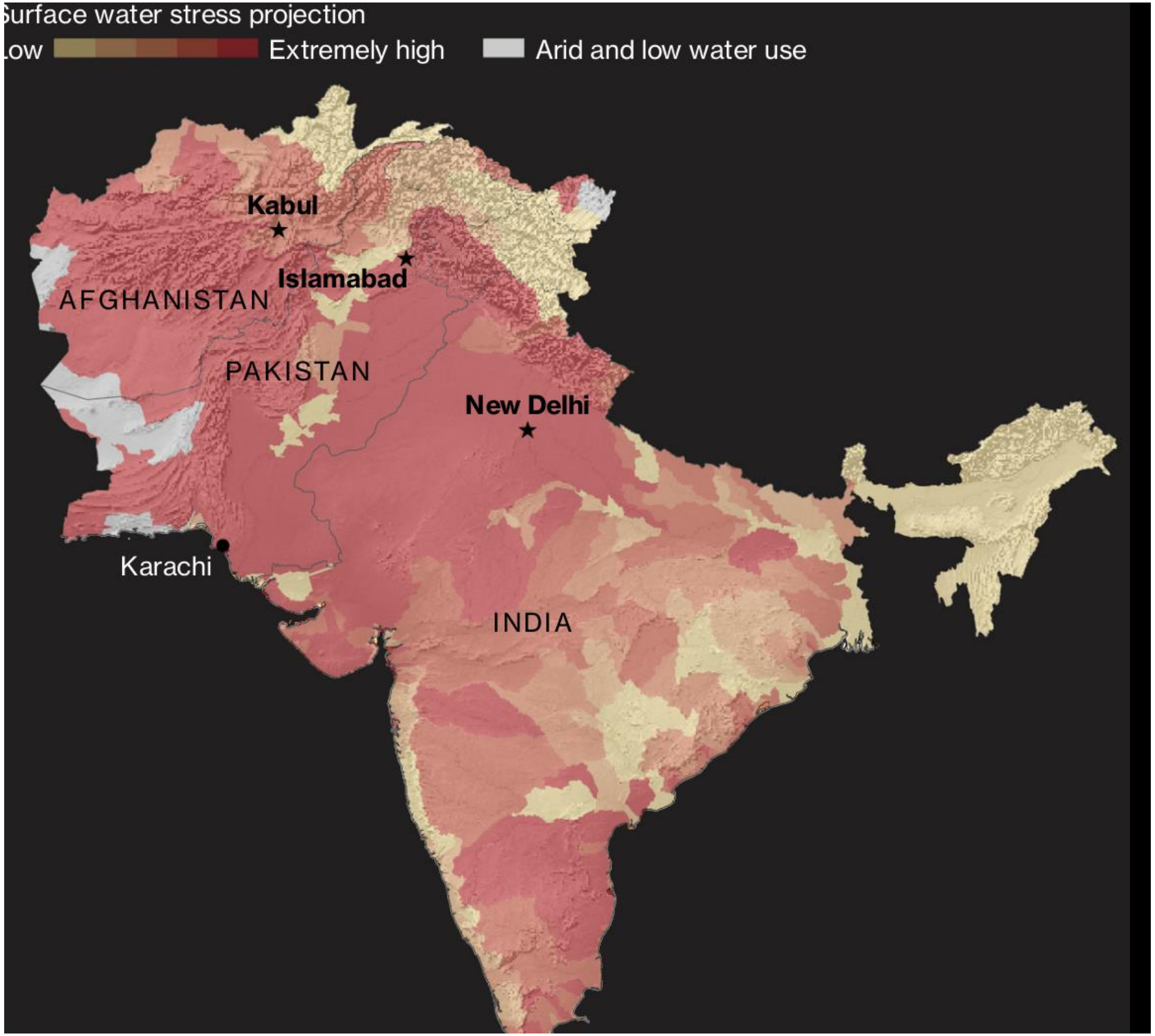
WATER

Water-scarce region

Declining water availability

Alarming groundwater depletion in India and Pakistan

Water crisis in Afghanistan



DISASTERS

Glacial lakes threaten people and economies

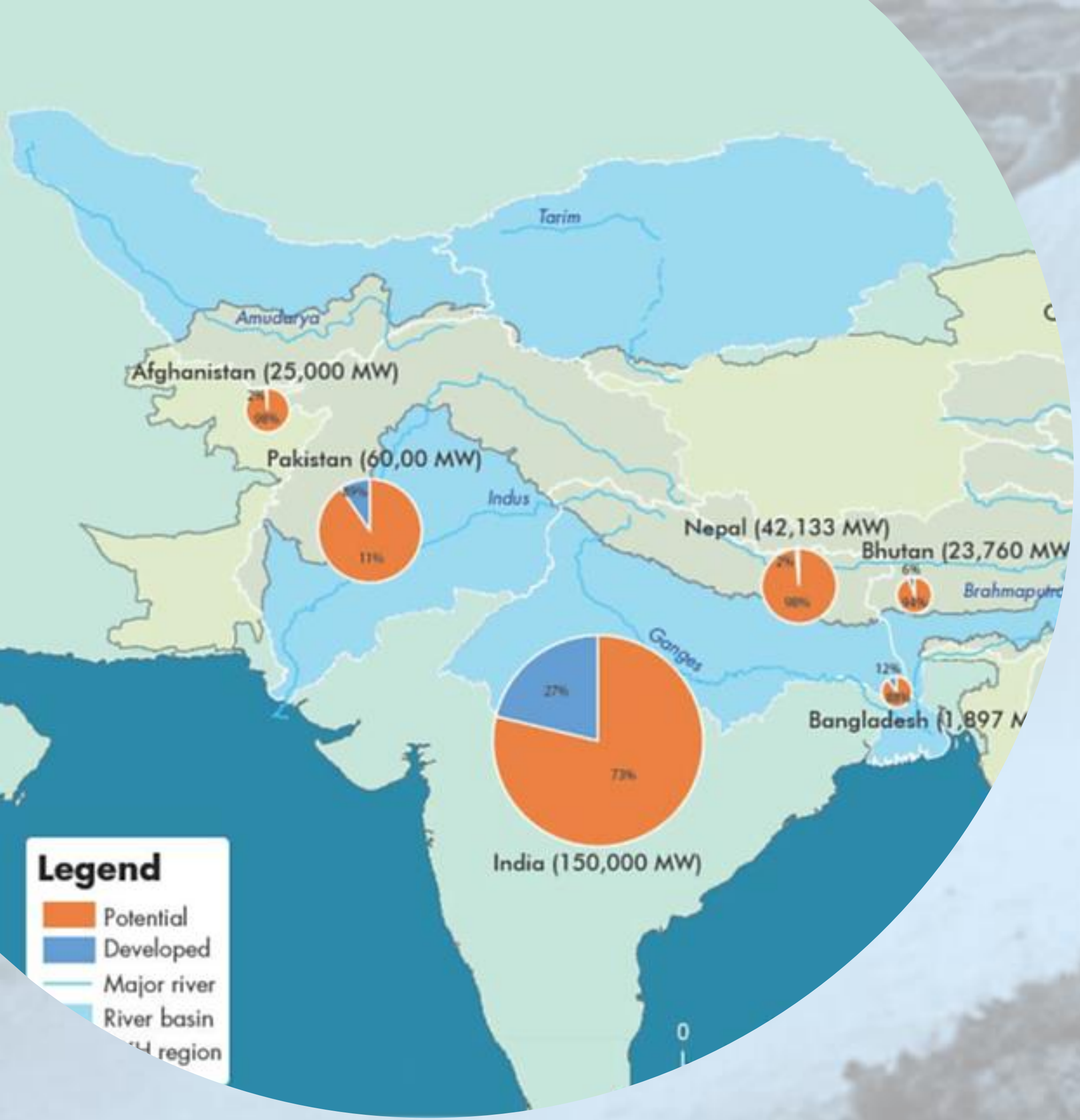
Floods and landslides

Water disasters cost billions annually in South Asia

FOOD

Changes to river flows and water supply

Impact on agricultural production both in mountains and downstream



ENERGY

500 million South Asians lack energy access

Huge hydro potential at risk

Disasters threaten hydro infrastructure

LIVELIHOODS & JOBS

Risks to livelihoods and jobs as tourism declines

Natural calamities destruct tourism infrastructure

8% of Nepal GDP depends on tourism

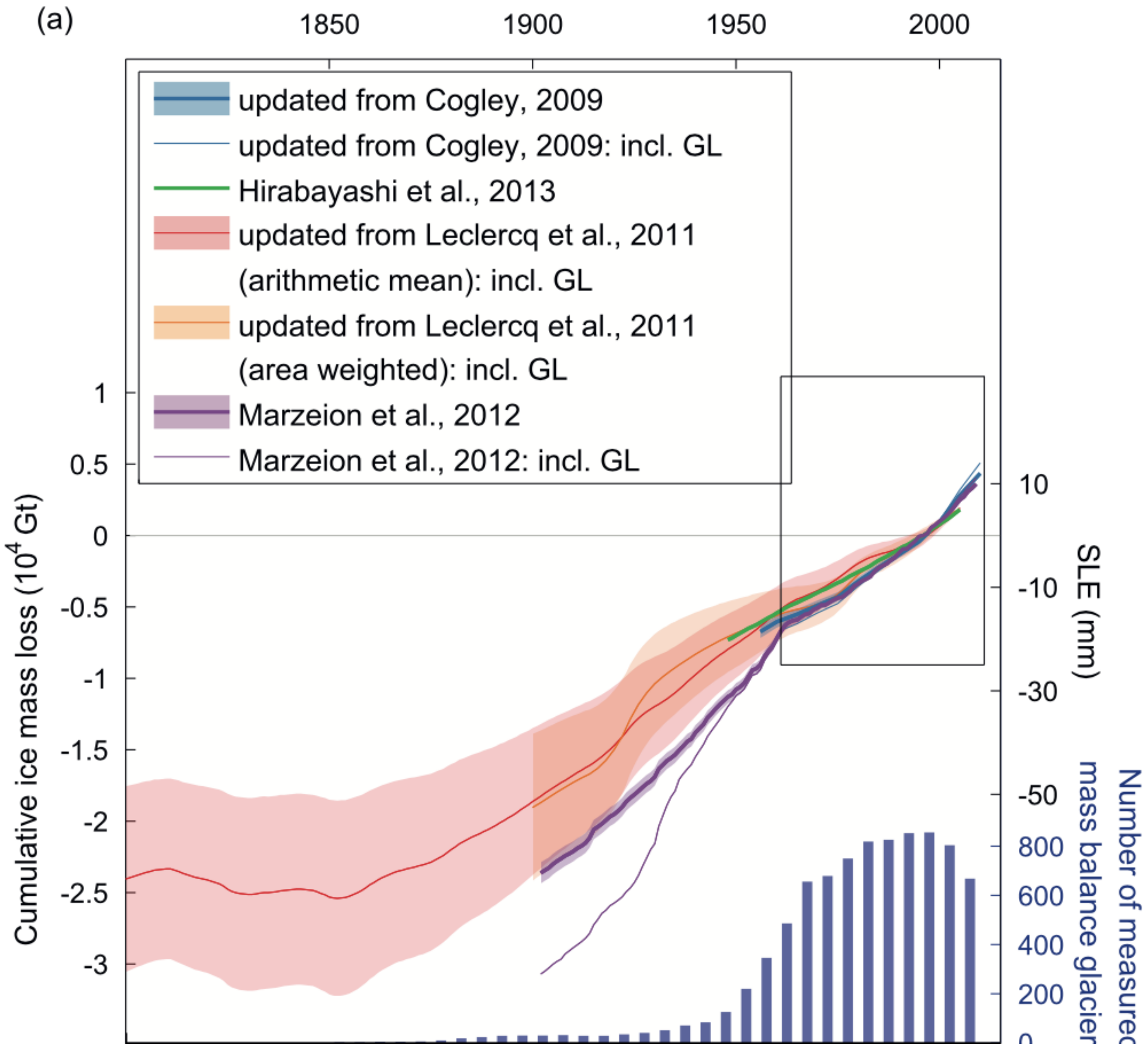

Ladakh
India

Glaciers of Himalayas

- **Span 3,500 km across eight countries**: Afghanistan, Pakistan, Nepal, India, Bhutan, Bangladesh, China, and Myanmar
- "**Roof of the World"** : contains all 14 of the world's highest mountains
- **The "Third Pole"** : contains the most glaciers in the world after the Artic and Antarctica
- **"Water Tower of Asia"** : the source of the 10 river systems that provide water to more than 210 million people in the mountains as well as roughly 1.3 billion people downstream

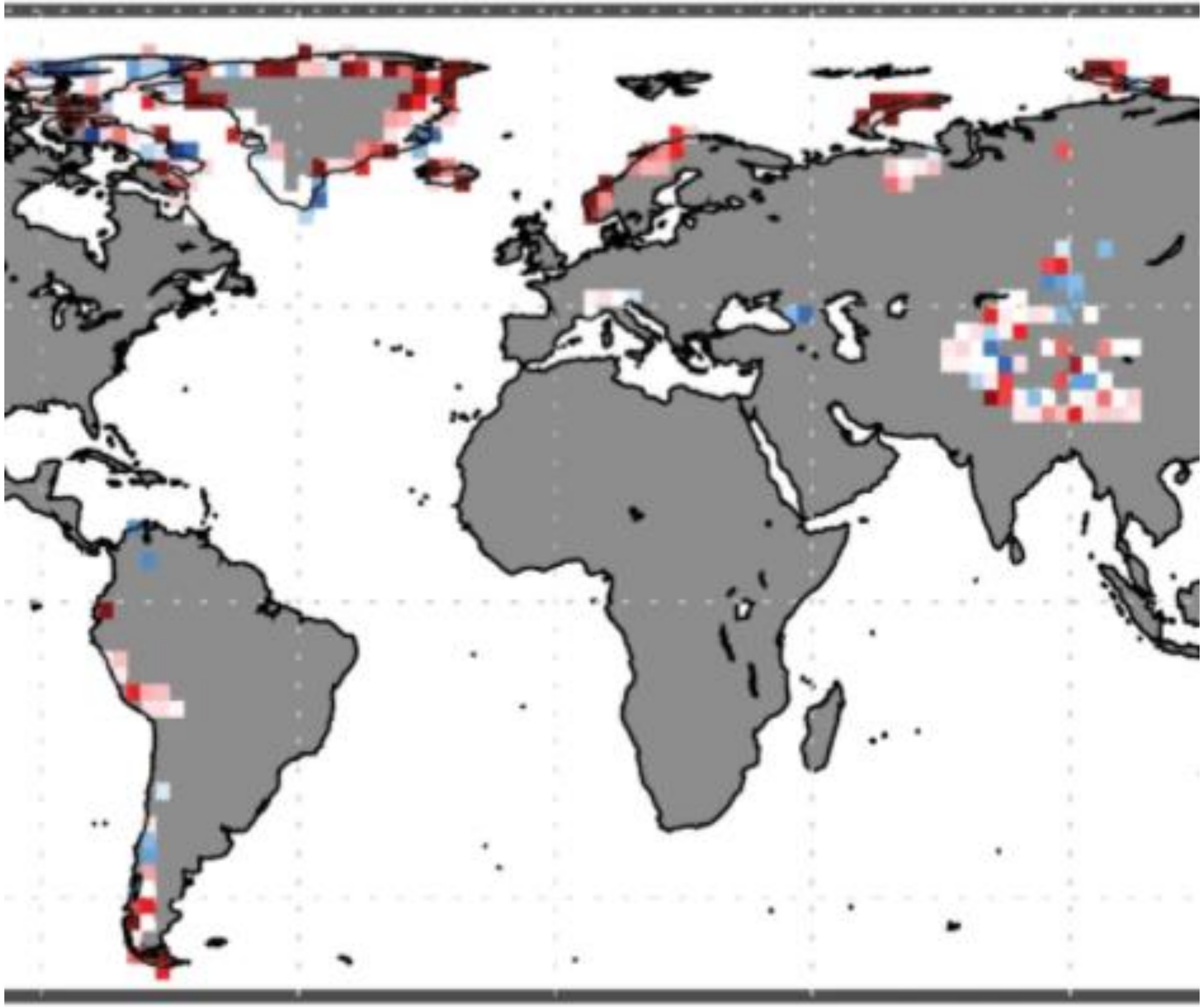
Cumulative glacier mass loss (10^4 Gt)

- Global cumulative glacier mass change for (whole period) 1801–2010 and (inset) 1961–2010. The cumulative estimates are all set to zero mean over 1986–2005.



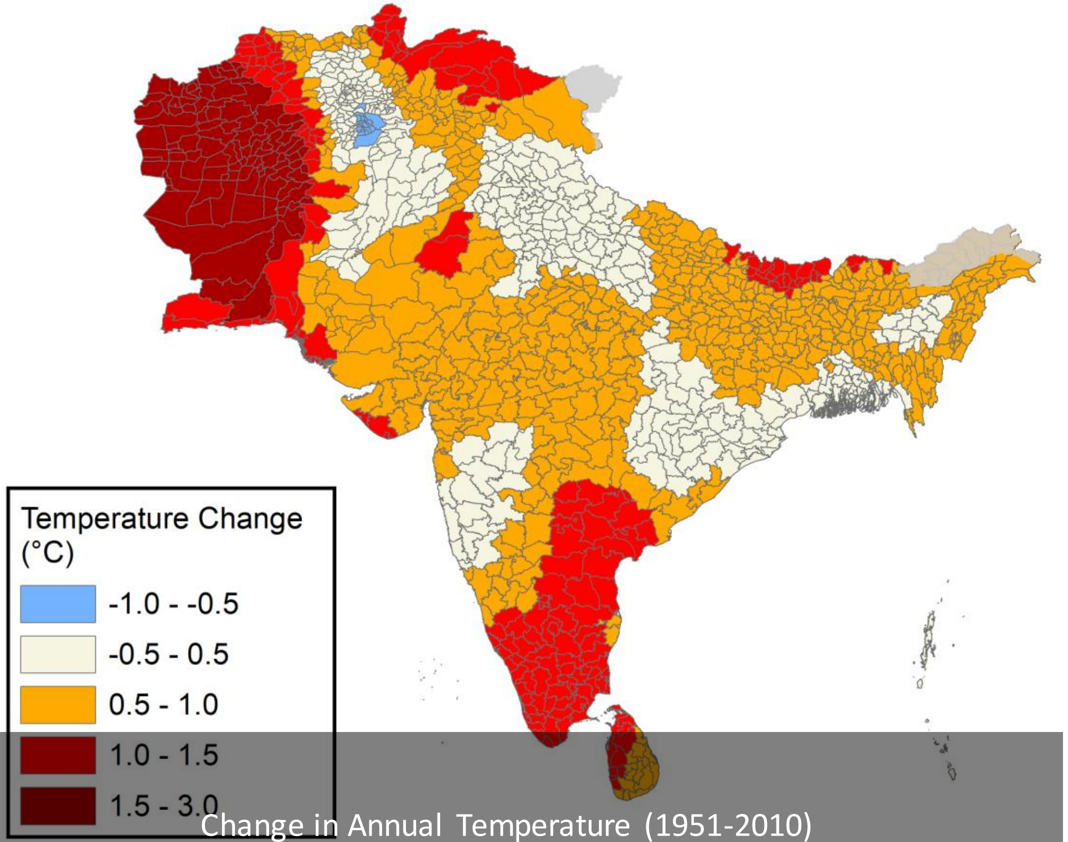
Glaciers melt, and glacier lakes enlarge

- Glacial lake volume change (absolute magnitude change), 1990-1999 to 2015-2018 (Shugar et al, *Nature Climate Change*, 2020)

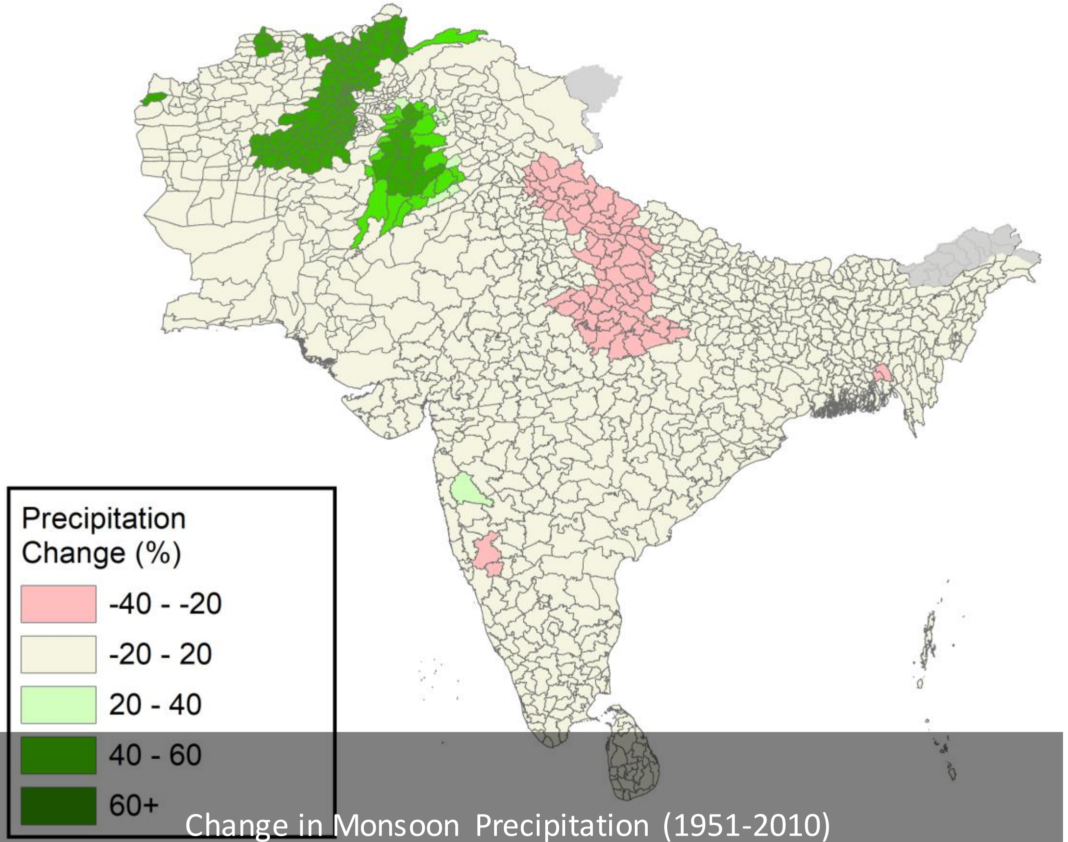


Glaciated HKHK region

Basin	Number of Glaciers	Glaciated area (km^2)	Estimated ice reserves (km^3)	Average area per glacier (km^2)
Amu Darya	3,277	2,566	162.6	0.8
Indus	**18,495**	**21,193**	**2,696.1**	**1.2**
Ganges	**7,963**	**9,012**	**793.5**	**1.1**
Brahmaputra	**11,497**	**14,020**	**1,302.6**	**1.2**
Irrawaddy	133	35	1.3	0.3
Salween	2,113	1,352	87.7	0.6
Mekong	482	235	10.7	0.5
Yangtze	1,661	1,660	121.4	1.0
Yellow	189	137	9.2	0.7
Tarim	1,091	2,310	378.6	2.1
Qinghai-Tibetan Interior	7,351	7,535	563.1	1.0
Total, HKHK	54,252	60,054	6,126.9	1.1



Change in Annual Temperature (1951-2010)

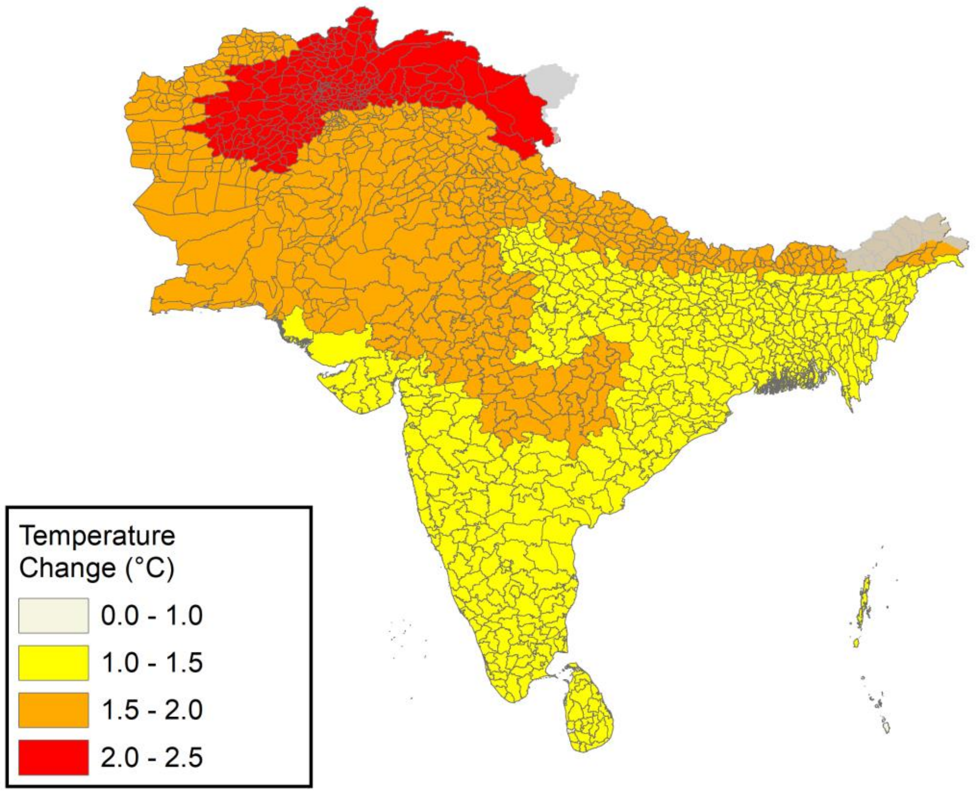


Change in Monsoon Precipitation (1951-2010)

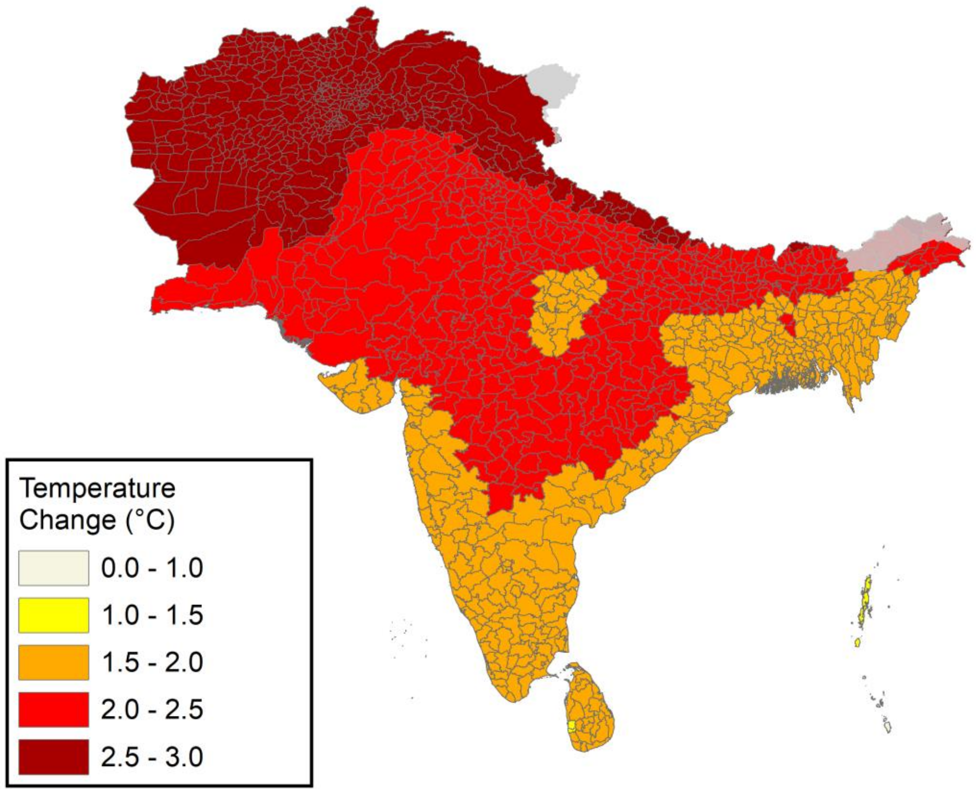
Unambiguous temperature increases (less so for precipitation)

Temperature increase will vary by location (by 2050)

Climate-sensitive (RCP 4.5)



Carbon-intensive (RCP 8.5)



Glaciers melt because of black carbon (BC)

Glaciers melt through changing climate

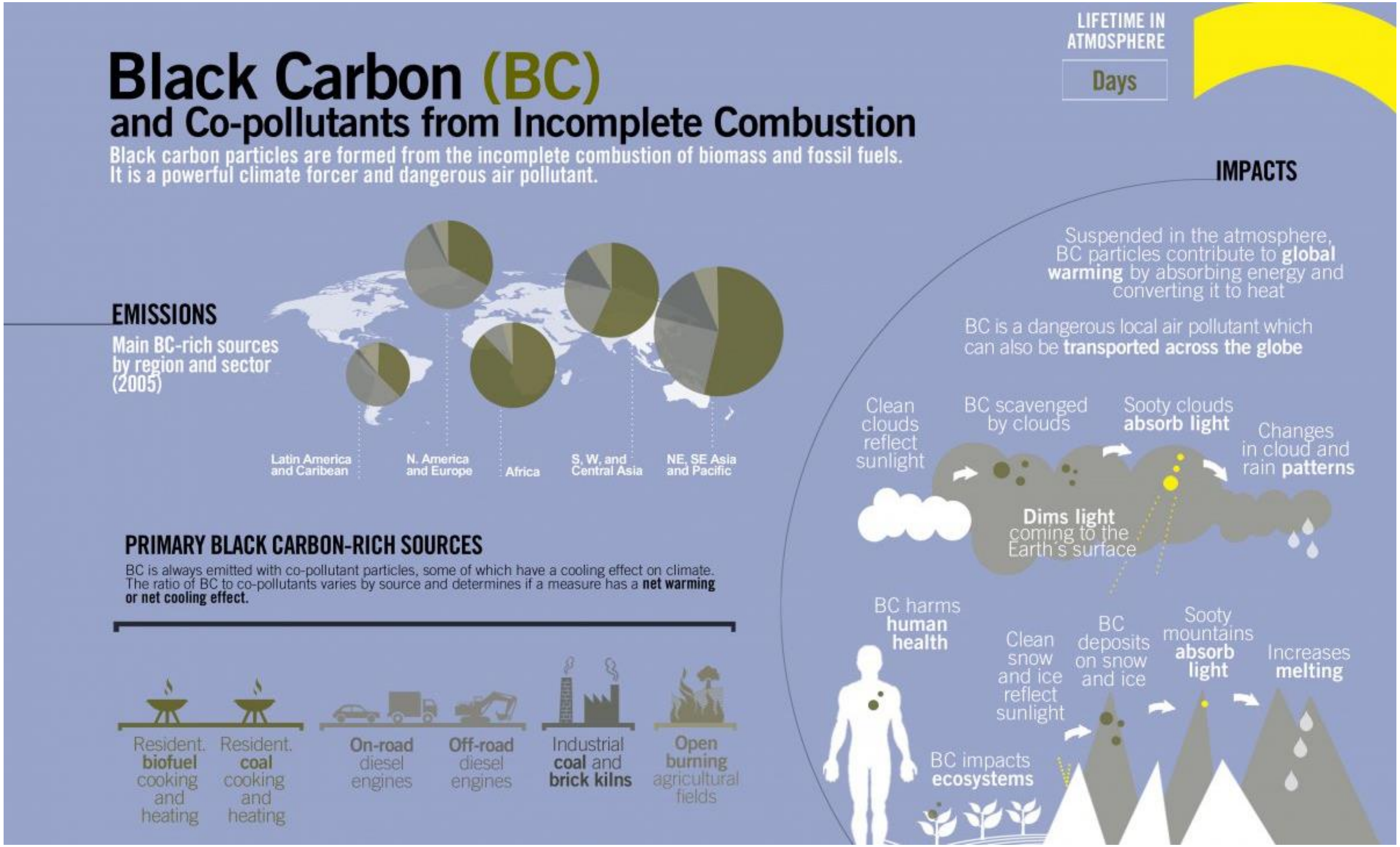
- Studies until recently regarded **changing temperatures and precipitation patterns** are major drivers of glacier melt.

Black carbon (BC) makes glaciers melt

- However, recent evidence suggests that **anthropogenic black carbon** deposition is further accelerating glacier and snow melt in the Himalayas.

BC is generated by human and economic activities

- BC is generated by human activity both within and outside of South Asia, and, unlike global climate change, may be meaningfully reduced by policy actions taken by the South Asian countries themselves. BC is viewed within a larger basket of aerosols that impact climate change processes both directly and indirectly.



Source: Climate and clean air coalition

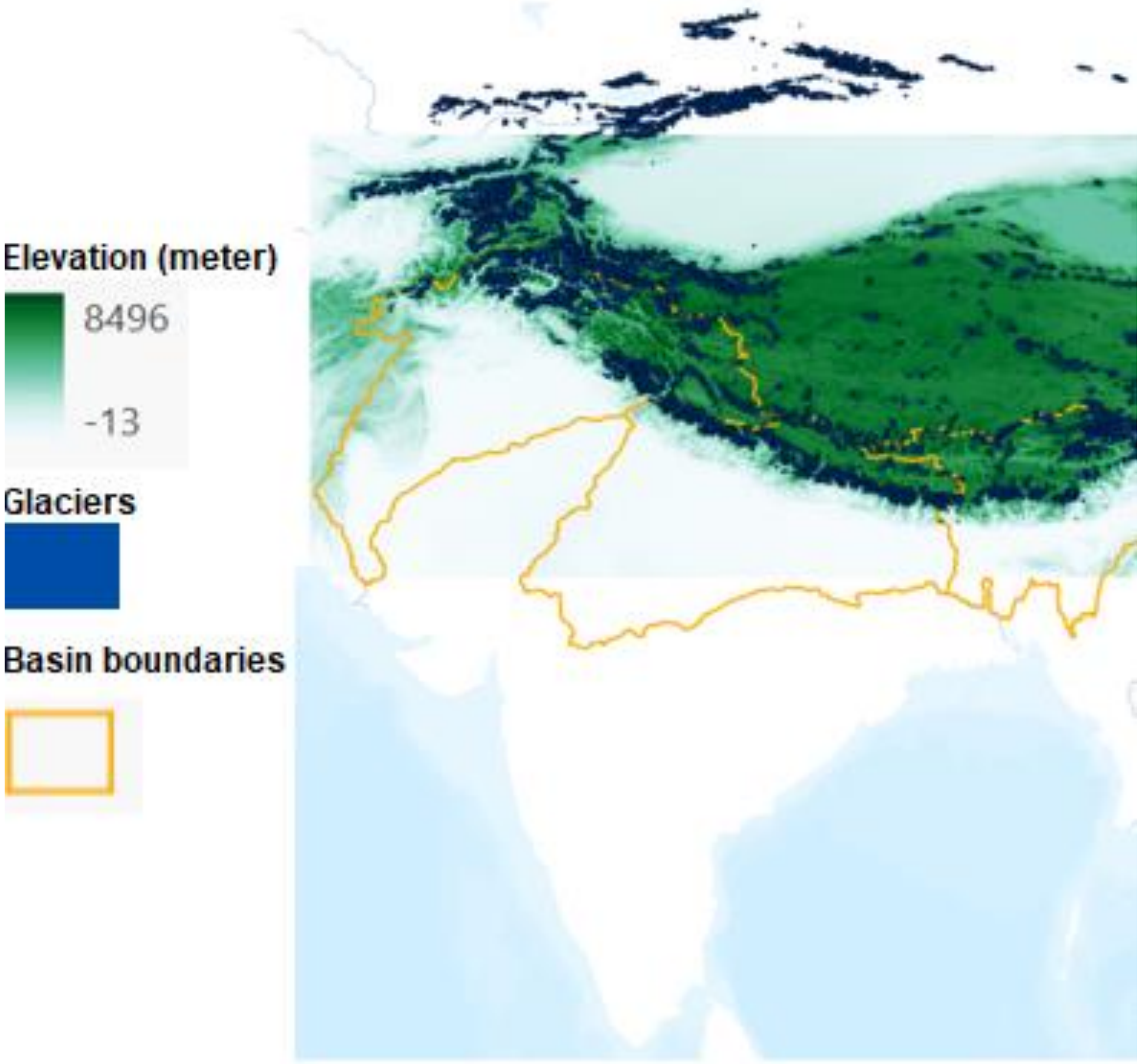
Main question and focus

BC and the HKHK

- The research question posed by this study is to what extent BC reduction policies undertaken by South Asian countries may impact glacier formation and melt in the Himalaya, Karakoram, and Hindu Kush mountain ranges (HKHK) within the context of a changing global climate, and to what extent water resources would be impacted by these glacial processes in downstream river basins (Ganges, Brahmaputra, Indus).

The HKHK region

- The Indus (left), Ganges (center), and Brahmaputra (right) Basins in South Asia.



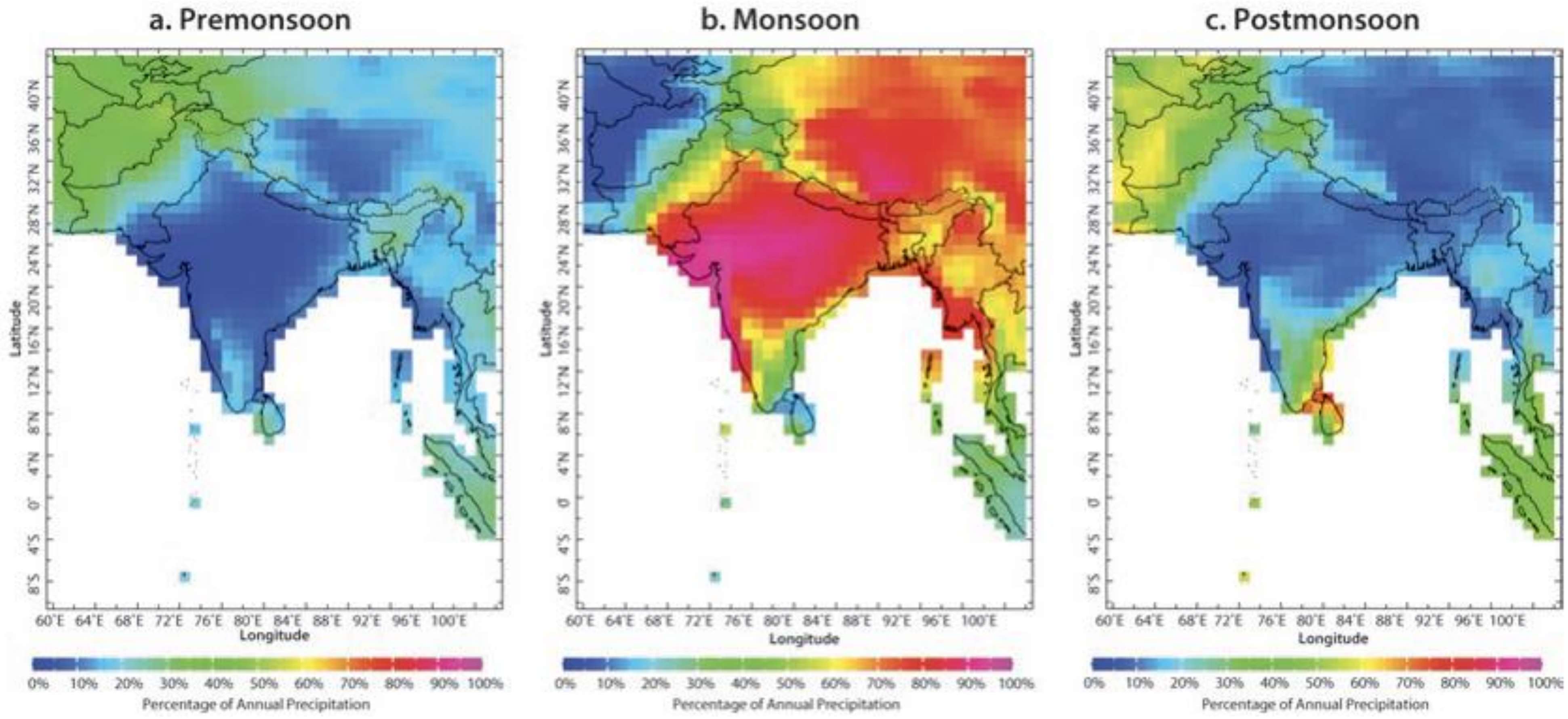
The hydrology of the GBI basins varies across several important parameters

- **Table on the right** summarizes key details for each river basin and shows the dependence of the watershed on upstream/downstream precipitation and of the resident population on the flow for irrigation.

- The table shows that **the Indus and Brahmaputra basins have extensive upstream areas** (i.e., above 2,000 meters)
- But the Ganges and Brahmaputra are generally wetter than the Indus. The Indus, however, is the most dependent upon its runoff for irrigation

Total area (km_2)	1,005,786	990,316	525,797
Total population (thousands)	209,619	477,937	62,421
Annual basin precipitation (mm)	423	1,035	1,071
Upstream area (percent)	40	14	68
Glaciated area (percent)	2.2	1.0	3.1
Annual upstream precipitation (percent)	36	11	40
Annual downstream precipitation (percent)	64	89	60
Irrigated area (km2)	144,900	156,300	5,989
Net irrigation water demand (mm)	908	716	480

The monsoon season brings most of the precipitation to South Asia

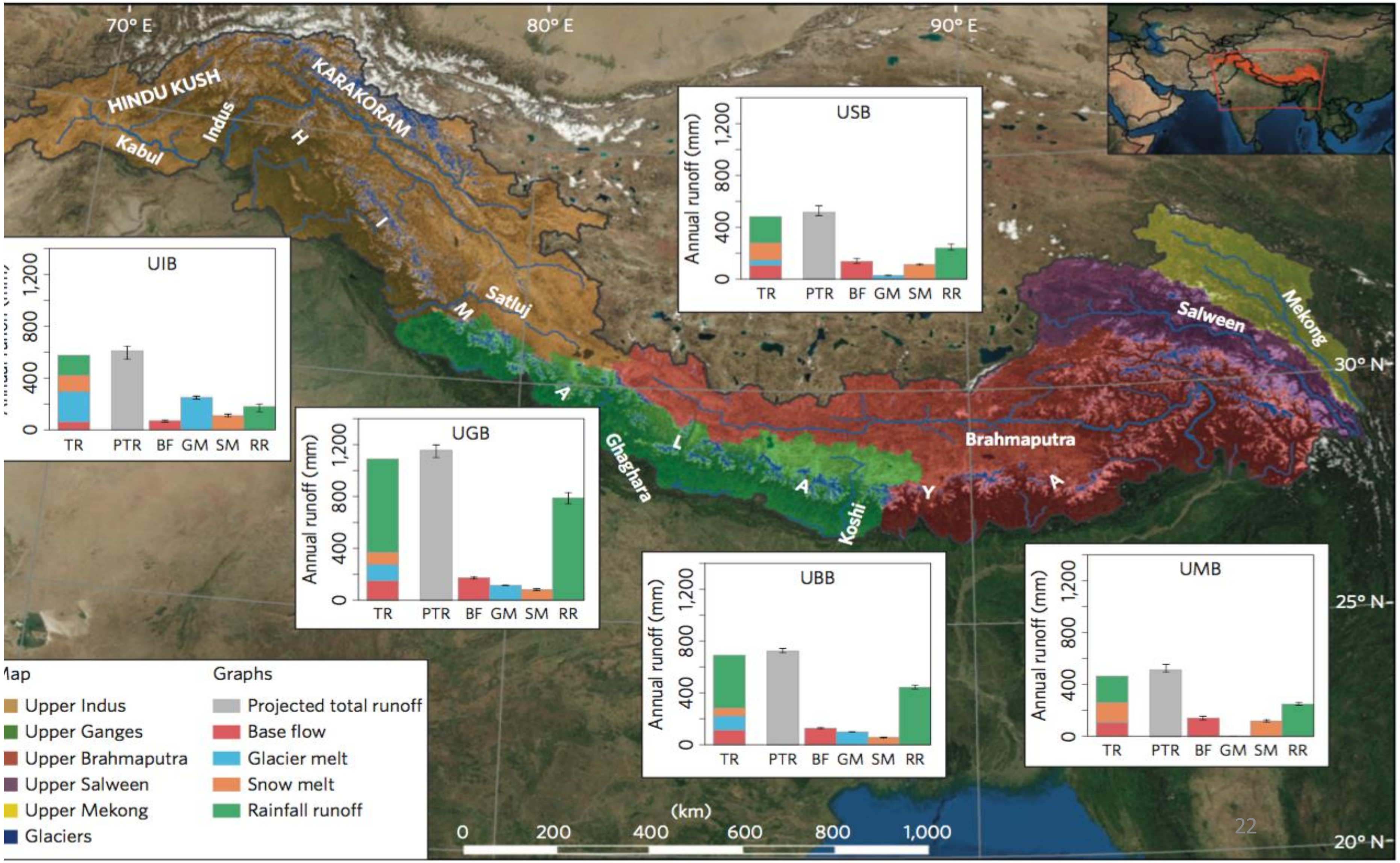


The contribution of snowmelt, glacier melt, and precipitation to overall runoff varies across basins

- The reduced contribution of precipitation to total runoff (green bars) in the Upper Indus relative to the Upper Ganges.

- Upper Brahmaputra indicates the reduced role of Monsoon precipitation.

- Glacial melt (blue bars) is a relatively larger contributor in the Upper Indus.



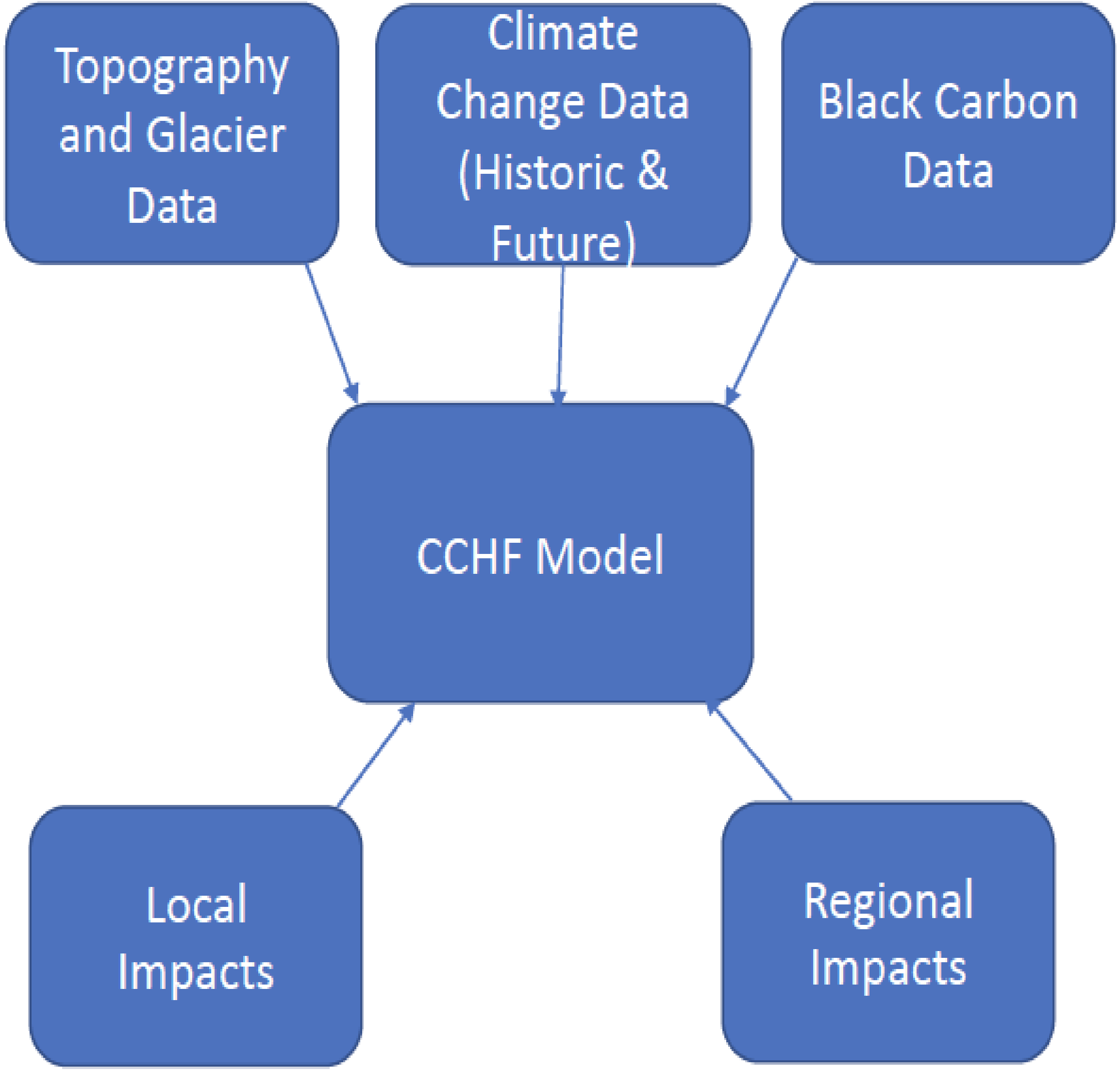
Methodology and data

- **New global climate model (GCM) simulations** are conducted with a low-aerosol (and BC) scenario in the context of RCP 4.5.

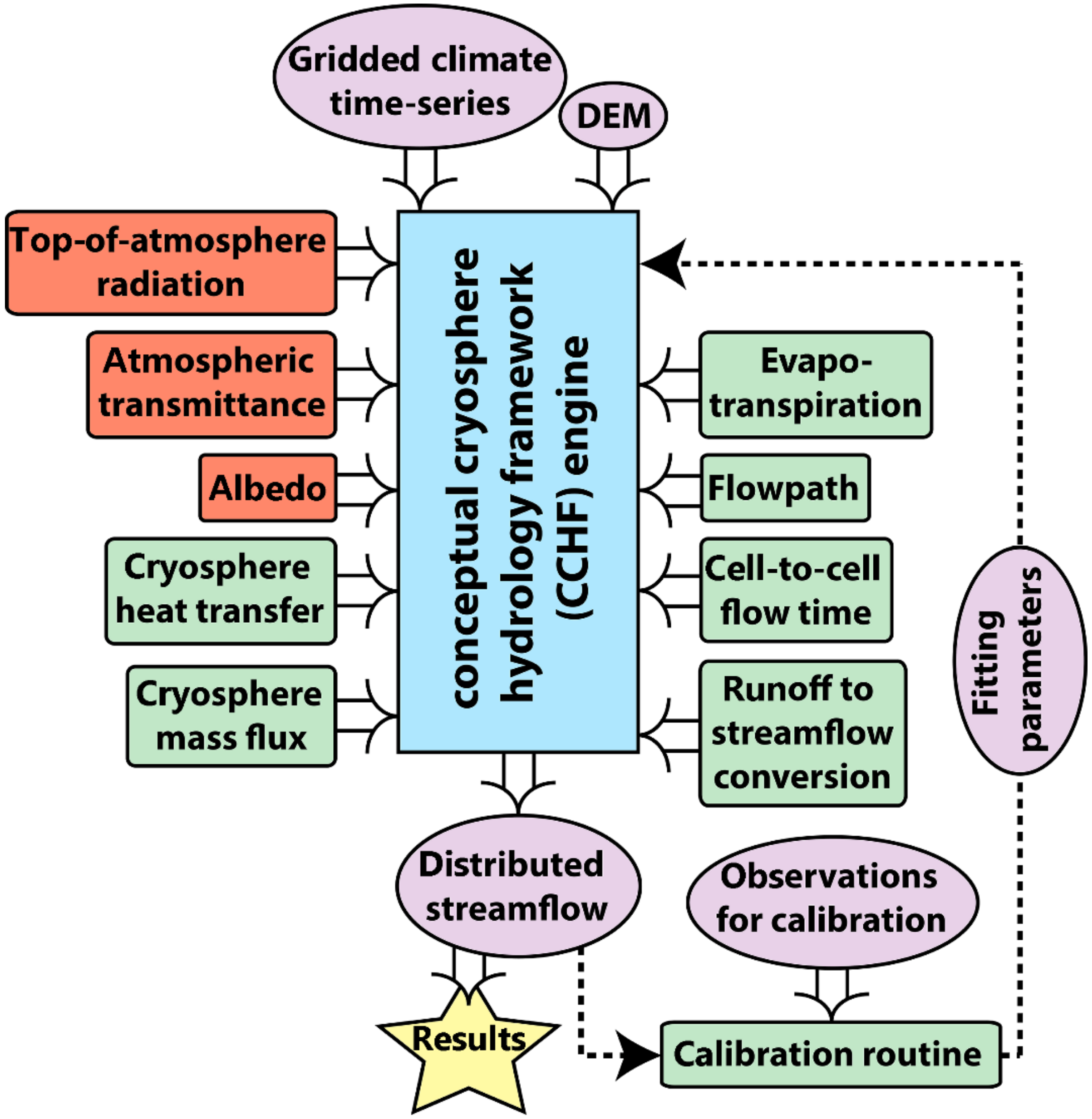
- The GCM outputs are then input to the **Conceptual Cryosphere Hydrology Model (CCHF).**

- **CCHF** simulates how these input scenarios impact water production, including rain runoff, snowpack formation and melt, and glacier formation and melt across the region.

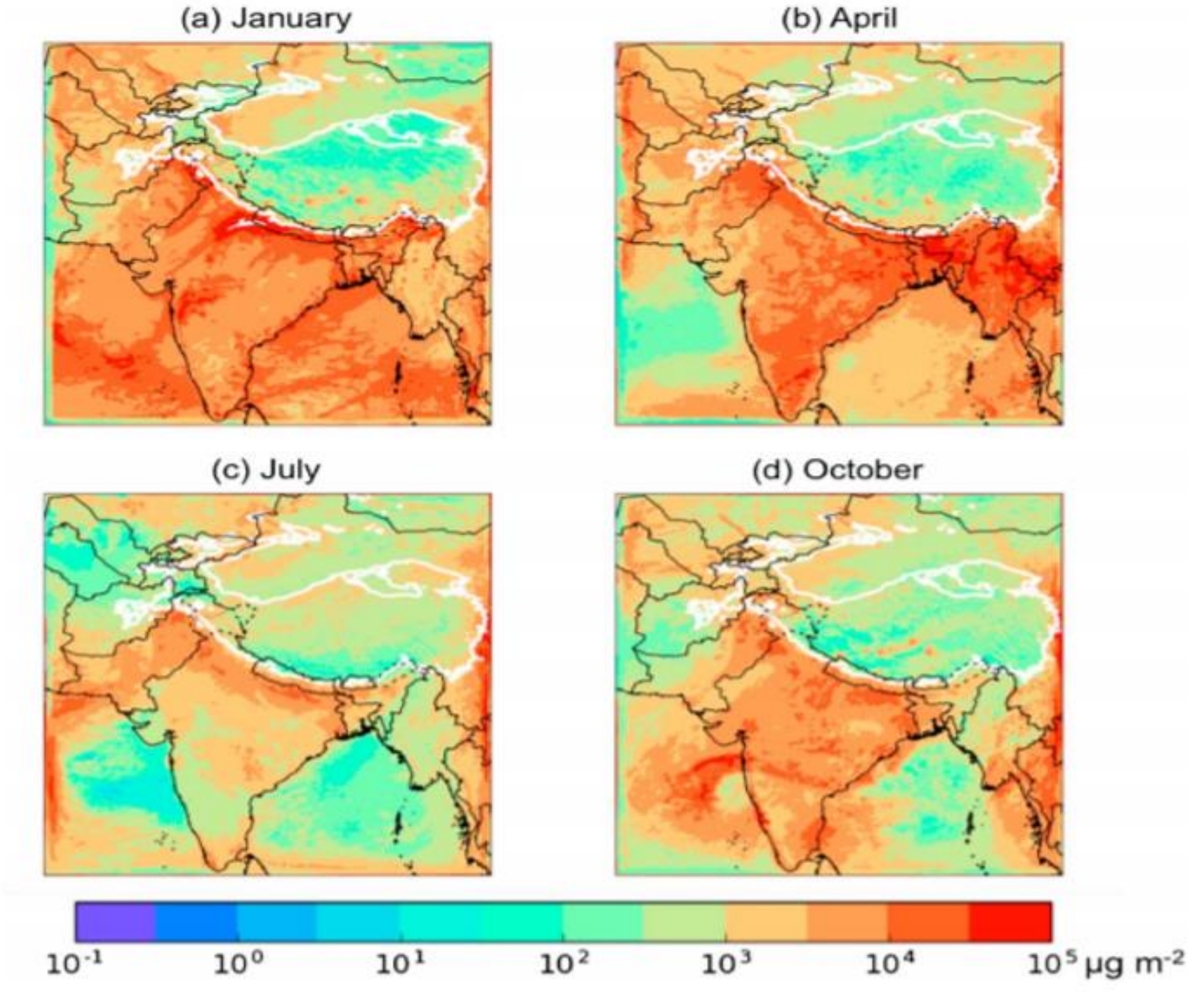
- **CCHF** includes physical representations of over 21 different physical processes constrained by the topography and initial glacier inventory and state (location, depth, and debris cover). **CCHF** also uses topography data and initial glacier properties (e.g. location, depth, and debris cover) as inputs.



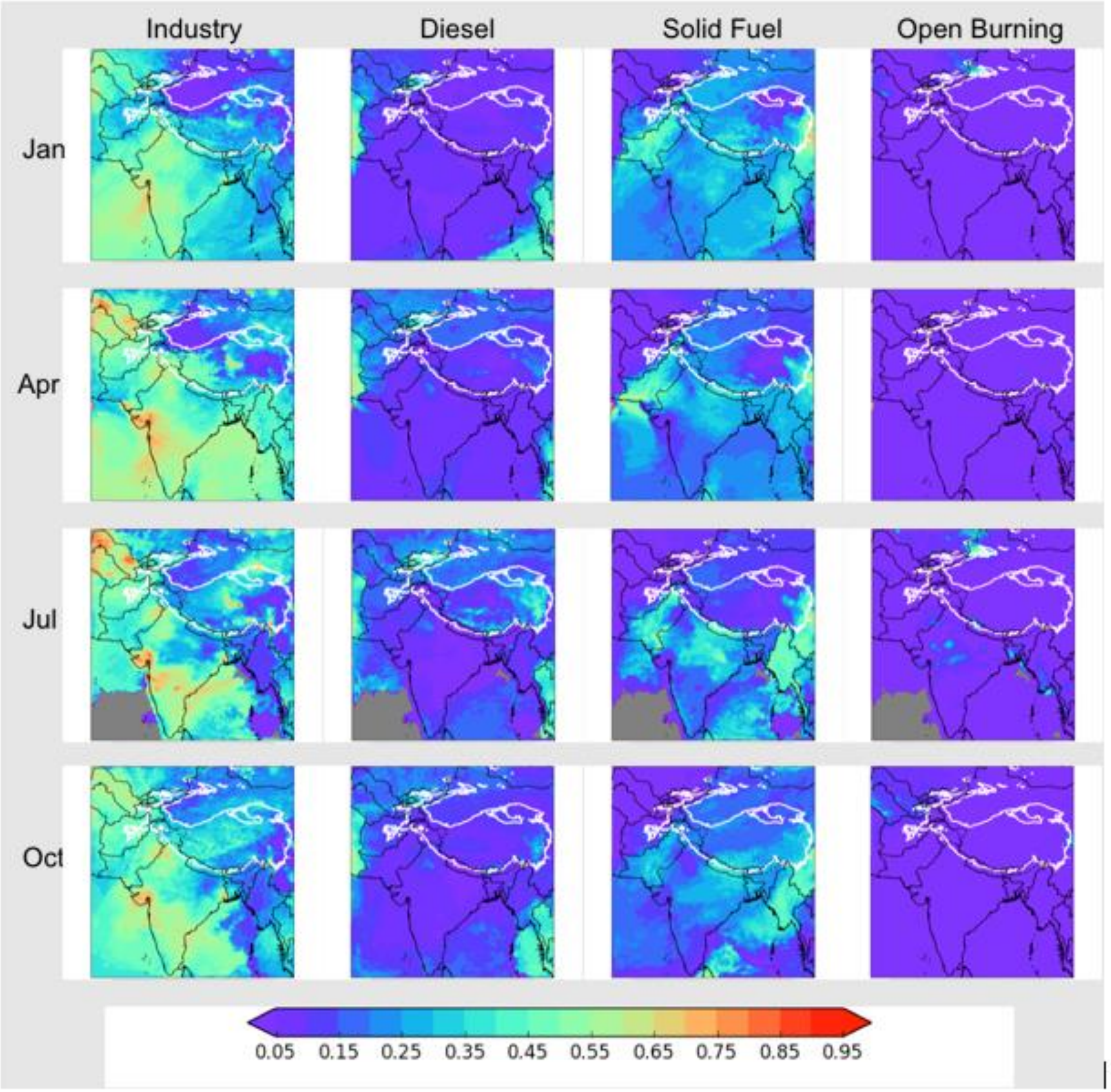
Model Structure



Significant variation in BC deposition across seasons



In-domain contributions to BC deposition in the HKHK



CCHF model: Linking climate, snow and glaciers and water resources

- CCHF assesses the impact of climate and BC emissions on the total water availability and in the distribution of water resources in the HKHK region **in the 2040s** relative to the reference **historical period (1985-2015).**
- **The model was calibrated** with streamflow observations, geodetic mass balance estimates and snow cover satellite imagery **at a 1 km spatial resolution and daily time step**.
- The model was validated with additional observations from these sites and subsequently used to produce the historic period (1985-2015) for the entire the HKHK region. The results for the last full decade constitute the baseline for analyzing the impacts of climate and BC emissions.

Water Runoff and Partitioning between Source by Basin during the Reference Period (2000-2010)

	Annual Precipitation (mm/year)	Annual Runoff (mm/year)	Contribution to total runoff (%)		
			Glacier melt (%)	Snow melt (%)	Rainfall Runoff (%)
Upper Ganges	1,350	1,296	4%	31%	66%
Upper Brahmaputra	1,981	1,932	3%	27%	70%
Upper Indus	789	796	10%	55%	35%

Runoff (mm / year) comparison across studies during the historical period

	This study (2000-2009)	Lutz and Immerzeel (2013) (1998-2007)	Armstrong et al. (2019) (2001-2014)
Upper Ganges	1,296	1,088	729
Upper Brahmaputra	1,932	691	1319
Upper Indus	796	574	657

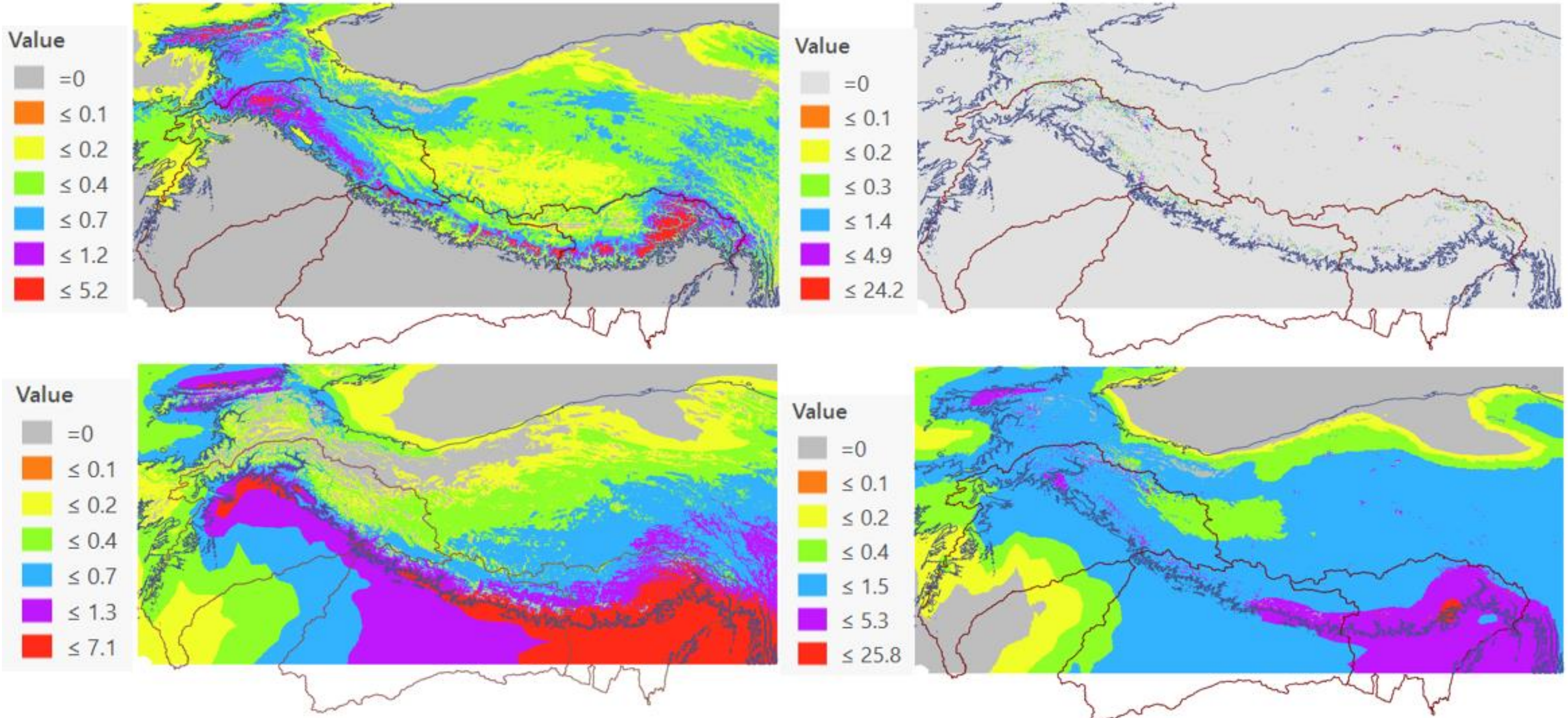
- **The total runoff results in this study are consistently higher than prior studies**, while there is considerable uncertainty around water production in the HKHK region.
- **Methodological differences** such as the use of imagery and isotope analysis in Armstrong et al. (2019) and a simple degree-index model in Lutz and Immerzeel (2013) **can partially explain some of the differences**.
- However, **precise comparisons of the results are confounded** by differences in the spatial extent and reference periods used in each of the studies.

Comparison of runoff partition estimates across studies

- The partitioning of runoff between ice melt, snowmelt and rainfall runoff in this study lies between prior estimates.

	Glacier melt			Snow melt		
	This study	Lutz and Immerzeel (2013)	Armstrong et al. (2019)	This study	Lutz and Immerzeel (2013)	Armstrong et al. (2019)
Upper Ganges	4%	12%	1%	31%	9%	47%
Upper Brahmaputra	3%	16%	<1%	27%	9%	73%
Upper Indus	10%	41%	3%	55%	22%	73%

The figure shows 1 km^2 Grid-level partition of water production (bottom right) between snow melt (top left), glacier and ice melt (top right), and rainfall runoff (bottom left) during the reference period (2000-2010)



- **Great spatial variations across indicators**: a large concentration of water production and rainfall runoff in Brahmaputra basin.

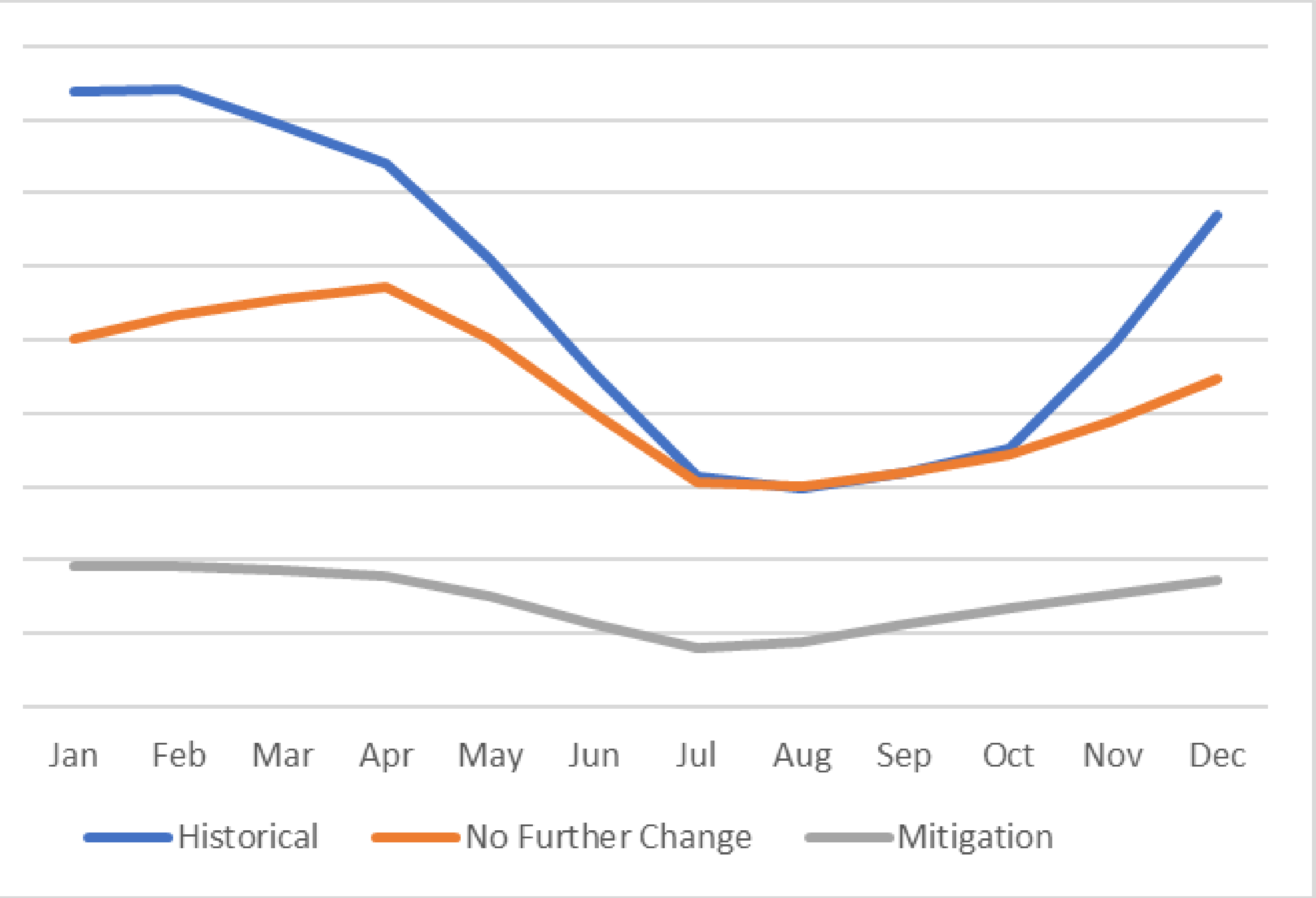
Black carbon deposition in the region

- **Black carbon deposition during the historic period is lowest during the summer rainy months** but gradually ramp up to nearly triple the minimum points in the summer.

- If fully implemented, **already-enacted black carbon emission polices are projected to reduce total annual black carbon deposits by 23%** across the region.

- Implementing **additional policy measures** that are currently technically and economically feasible **could reduce the black carbon deposits by an additional 50%.**

- **Seasonality of deposition** matters for snow since the snowpack "refreshes" when new snow falls and each year when the snow melts. **Seasonality of deposition** on glacier surfaces matters less.

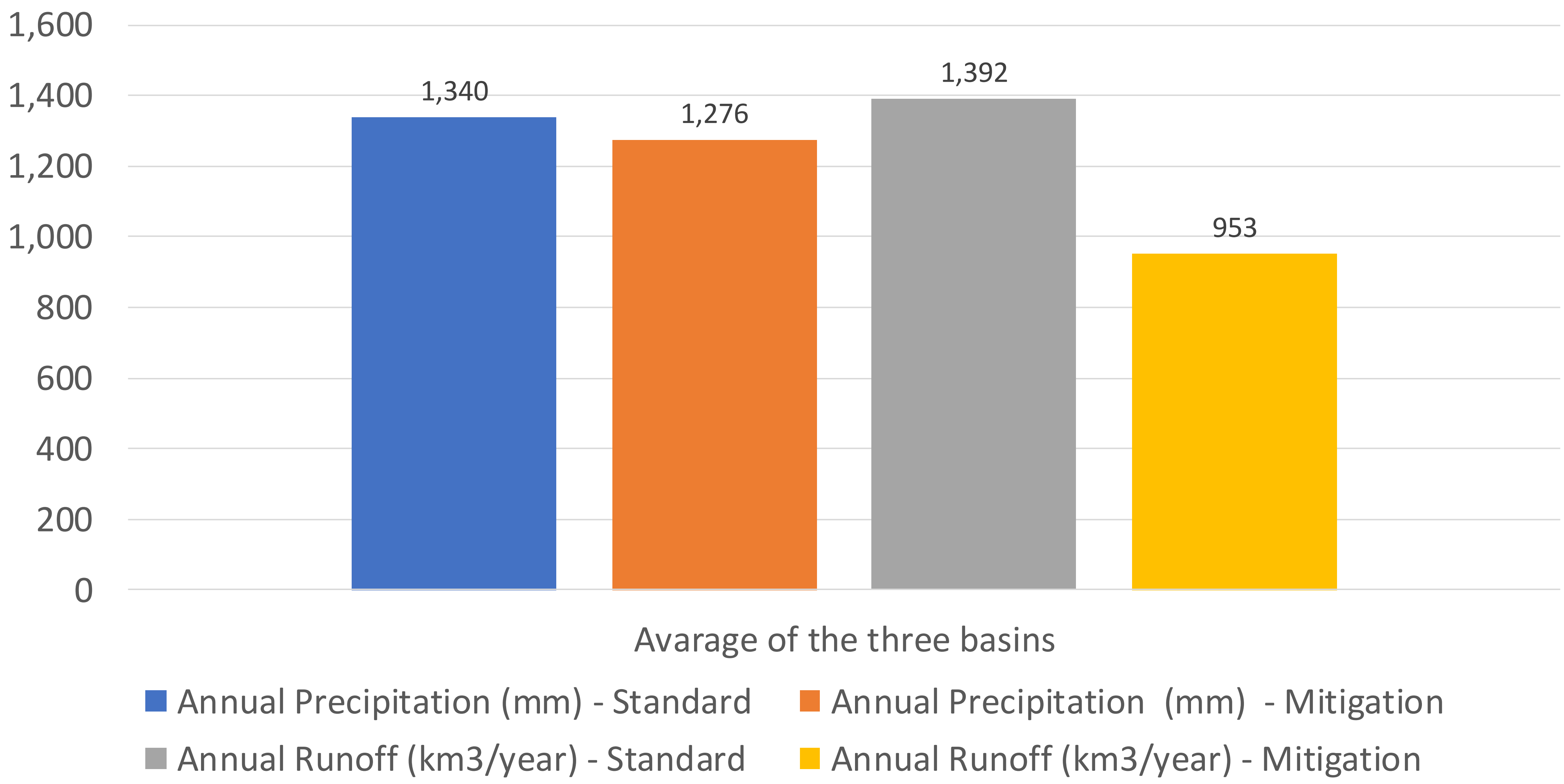


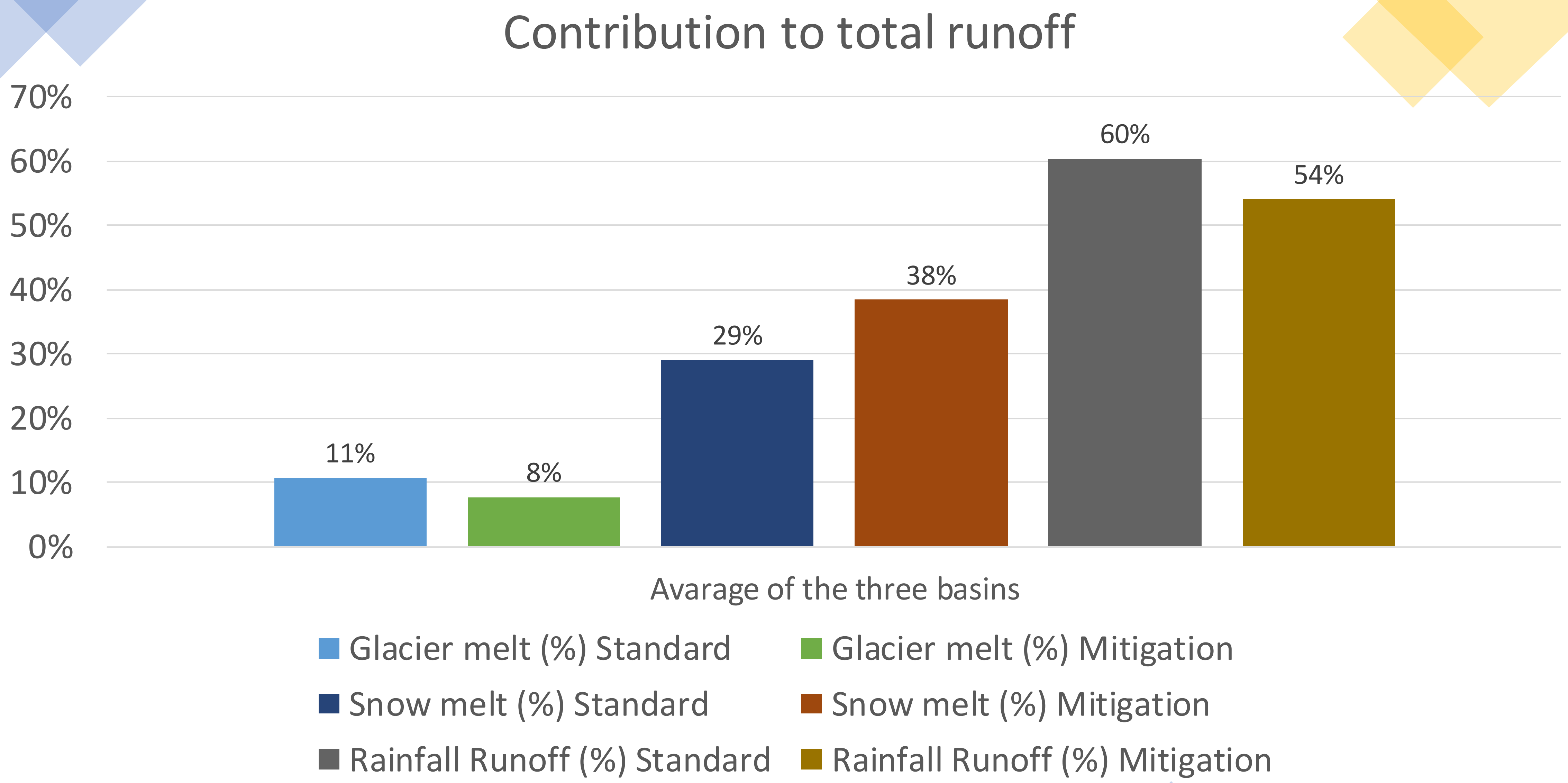
Note: The modelled black carbon deposition data used as an input to CCHF model simulations were developed from simulations of the WRF-CHEM model.

Comparison between the standard case vs the mitigation case

- The table shows the **RCP standard case** and the **RCP aerosol mitigation case in the 2040 results**.
- According to the results of ensemble means for total precipitation/runoff as well as the contribution from each source, **black carbon polices in South Asia have clear measurable impacts on future water resource availability and water resource use planning**.

	Annual Precipitation (mm)		Annual Runoff (km^3/year)		Contribution to total runoff (%)					
					Glacier melt (%)		Snow melt (%)		Rainfall Runoff (%)	
	Standard scenario	Mitigation scenario	Standard	Mitigation	Standard	Mitigation	Standard	Mitigation	Standard	Mitigation
Upper Ganges	1,246	1,164	1,329	894	11%	9%	20%	27%	69%	64%
Upper Brahmaputra	1,927	1,891	1,915	1,426	5%	4%	22%	29%	73%	67%
Upper Indus	846	772	932	540	16%	10%	45%	59%	39%	31%


1,600
1,400
1,200
1,000
800
600
400
200
0
1,340
1,276
1,392
953
Avarage of the three basins
Annual Precipitation (mm) - Standard
Annual Precipitation (mm) - Mitigation
Annual Runoff (km3/year) - Standard
Annual Runoff (km3/year) - Mitigation


Contribution to total runoff
70%
60%
50%
40%
30%
20%
10%
0%
11%
8%
29%
38%
60%
54%
Avarage of the three basins
Glacier melt (%) Standard
Glacier melt (%) Mitigation
Snow melt (%) Standard
Snow melt (%) Mitigation
Rainfall Runoff (%) Standard
Rainfall Runoff (%) Mitigation

Summary of main findings

- South Asian countries **can reduce BC deposition** in the region **by 23% by implementing policies currently in place** and **by a further 50% by enacting and implementing new policies** that are currently economically and technically feasible.

- **Full implementation of current BC emissions policies in South Asia is projected to increase water releases from glacier melt** in absolute volume and as a share of the total water production in the 2040’s in the upstream areas of the Ganges, Brahmaputra and Indus basins.

- Enacting additional technically and economically feasible **BC emission reduction polices can reduce glacier melt to current levels**, but it **may also reduce water supplies and exacerbate water stress**.

Conclusions

- **Melting glaciers pose significant risks to the stability of water resources in the South Asia region** with implications on local, national and regional economies.
  - South Asia is **highly dependent** on water provided by the region's **glaciers**, making the region **highly vulnerable** to the challenge of **climate change**.
  - Future projections of climate change and **black carbon** for the region suggest that **rising temperatures** and **deposition of black carbon** will continue to impact on snow and glacier dynamics.

- This report set out to understand **whether regional black carbon policy could make a difference** at protecting South Asia's water towers in the context of global climate change.

Conclusions (cont.)

- **Melting glaciers, loss of seasonal snow and precipitation changes pose significant risks to the water resources** in the South Asia region and will only get worse.
  - Glaciers help to moderate river flows in the region's major rivers by providing a source of meltwater in hot, dry years and storing water during colder, wetter years.
  - The dependence on glaciers and snow make these rivers particularly vulnerable to climate change.

- **Regional cooperation can be an effective transboundary solution**, helping countries in the HKHK manage glaciers and related natural assets collaboratively.

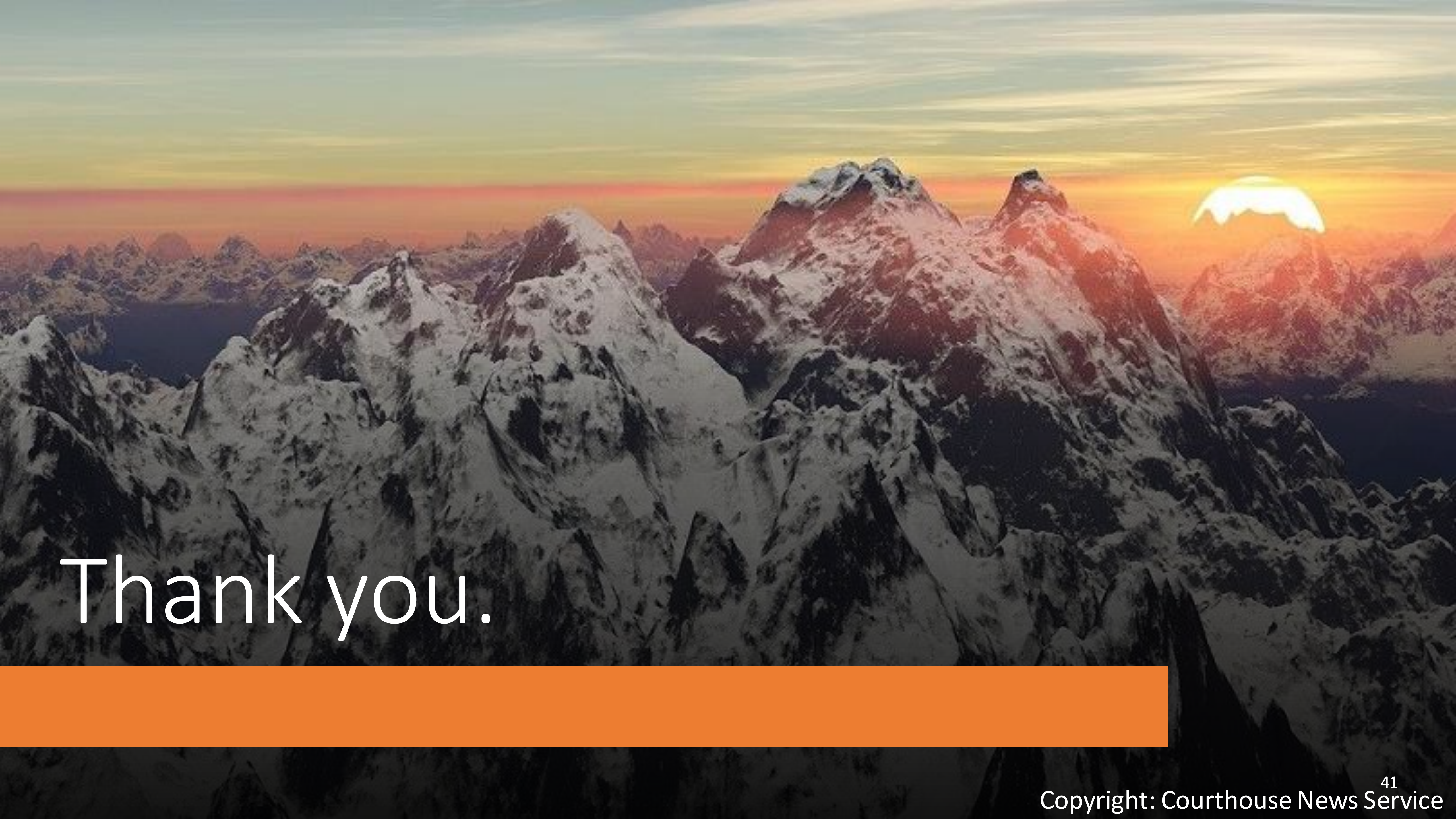
Conclusions (cont.)

- **Managing black carbon is critical to managing the region's water resources.**
  - **A key message** emerging from this report is that **reducing atmospheric concentrations of black carbon in South Asia has significant implications for the future of water resources** in the region. In addition, it can result in improved public health and a slowing of the rate of near-term climate change.
  - The findings suggest that **black carbon has not only historically played a role in snow and glacier dynamics** in the headwaters of the Indus, Brahmaputra, and Ganges basins, **but will increasingly play an important role in glacier and snowmelt unless managed effectively**.

Conclusions (cont.)

Further perspectives need to be considered, too…

- *Global climate change driven by greenhouse gases is also driving extensive changes to the region's water resources.*
- *Improving the efficiency of brick kilns could be key to managing black carbon.*
- *Transition to cleaner cookstoves will have multiple benefits.*
- *Mountain communities are particularly vulnerable*.
- *Glacier lake outburst floods (GLOFs) pose serious threats.*
- *The South Asia region needs to carefully manage its hydropower and storage resources*.



Thank you.