Supplementary Information for the article "Diagnosing Aerosol-Meteorological Interactions on Snow within the Earth System: A Proof-of-Concept Study over High Mountain Asia"

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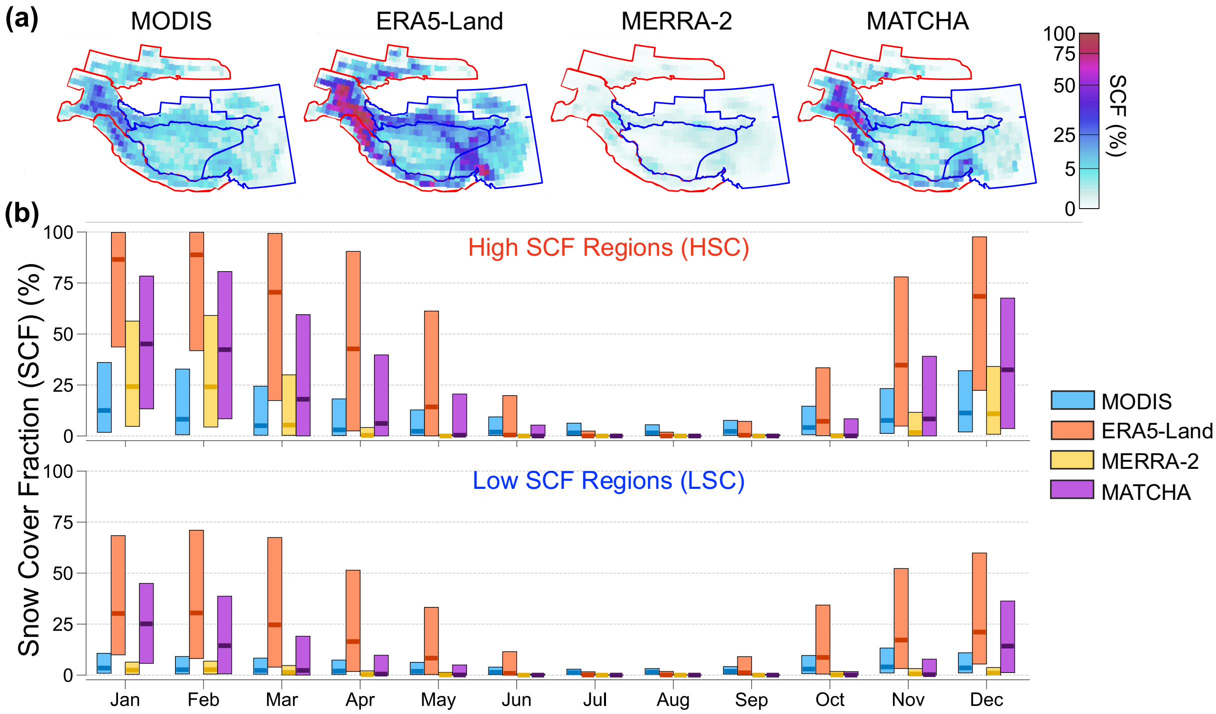
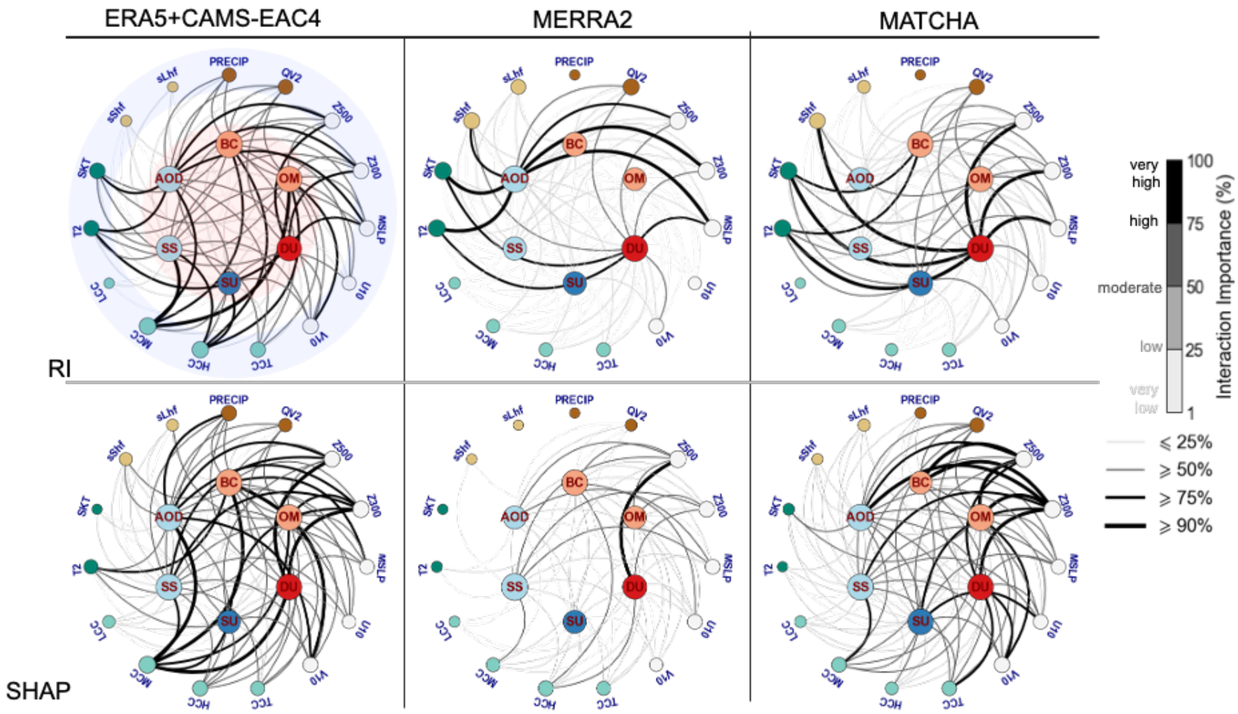
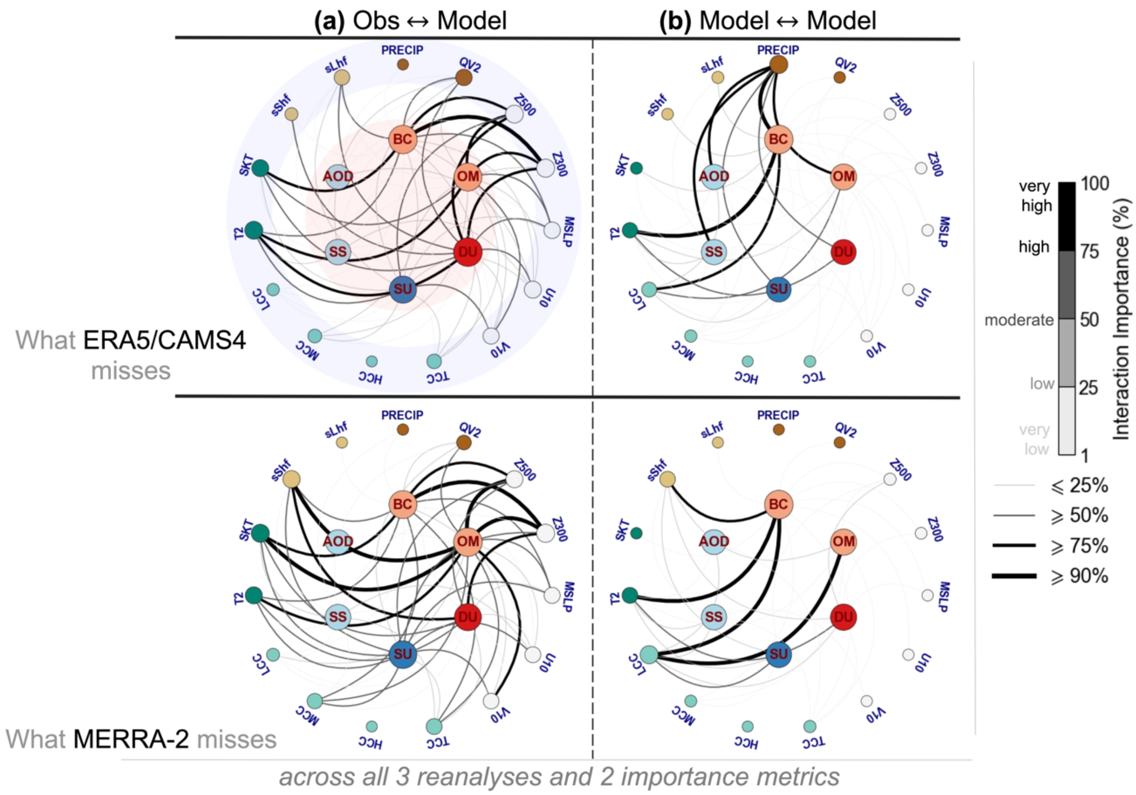


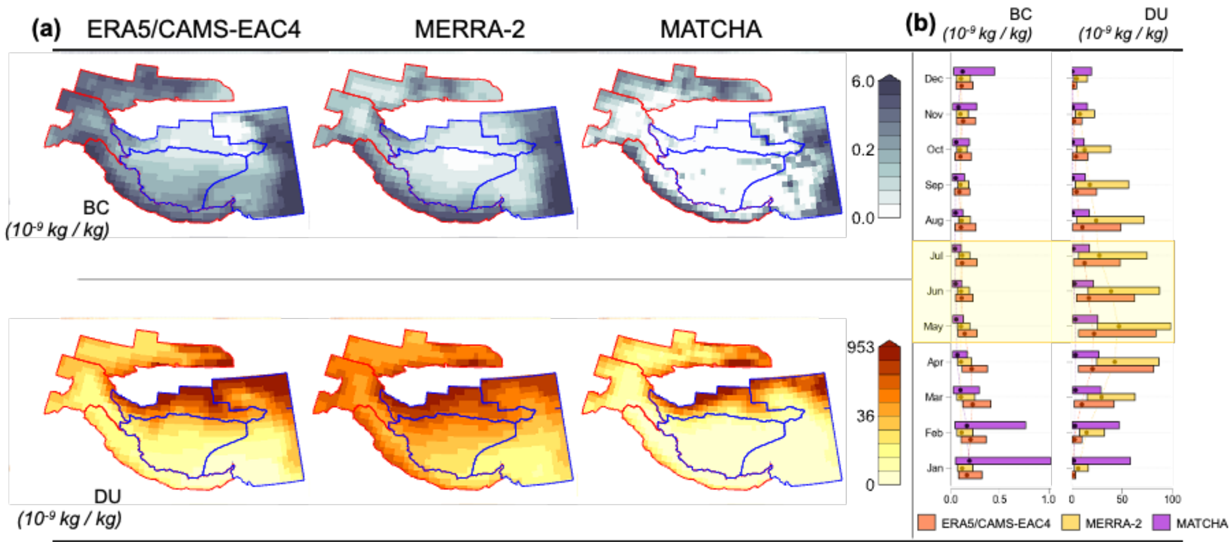
Supplementary Figure 1. Spatio-temporal distribution of snow cover fraction over HMA. (a) Temporal average (2003-2018) of snow cover fraction at 0.75° resolution during the late snowmelt season (May - July) with geographical outlines from RGI v6. Blue regions denote low snow cover (LSC) regions, while red regions denote high snow cover (HSC) regions. The LSC regions are composed of the following second-order regions based on the Randolph Glacier Inventory v6.0, 1) Inner Tibet, 2) S and E Tibet, 3) Hengduan Shan, 4) Qilian Shan, 5) W and E Tien Shan, 6) W and E Kun Lun. The HSC regions are composed of the following second-order regions, 1) W, C, and E Himalayas, 2) Hindu Kush, 3) Karakoram, 4) Pamir, and 5) Hissar Alay. (b) Monthly time series of snow cover fraction (SCF) across low and high snow cover regions from three reanalysis datasets and MODIS. The height of the bars represents the interquartile range (IQR) with the median.



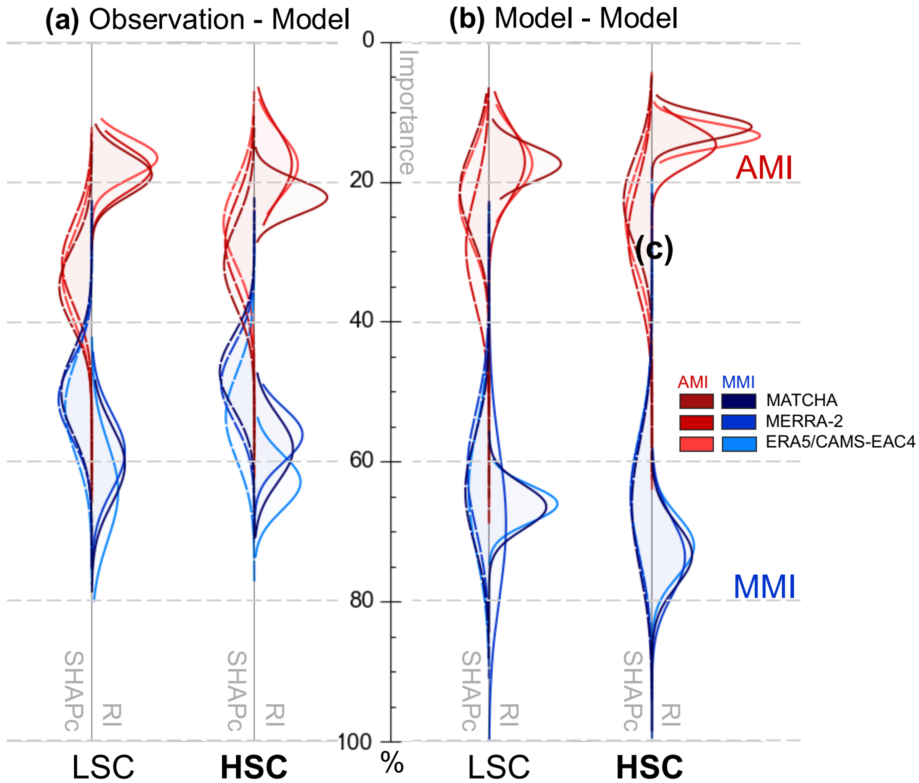
Supplementary Figure 2. **Underrepresented aerosol-meteorology interactions for all three reanalyses and each importance metric.** Network diagrams depicting the underrepresented interactions (positive difference in interaction importance from Obs-Model construct and Model-Model construct) for three reanalyses (across columns) and the importance metrics (across rows). The nodes are arranged in a concentric fashion, with the innermost nodes representing aerosol predictors (highlighted with light red shading) and the outermost nodes representing meteorology predictors (highlighted with light blue shading). The interaction importances are shown through edges connections/lines between the nodes and are weighted by colors and width denoting the strength of the importance (1 to 100%, very low-low for <=25%, low-moderate for 25% to 50%, moderate-high for 50% to 75%, and high-very high for >=75% shown in the color bars).



Supplementary Figure 3. Underrepresented interactions that ERA5/CAMS4 and MERRA-2 fail to show relative to MATCHA. Network diagrams depicting the underrepresented interactions in both reanalyses compared to MATCHA aggregated across both RI and SHAPc metrics for (a) Obs-Model and (b) Model-Model construct. The interaction importances are based on aerosol-meteorology interactions onto snow (AMI) in low snow-cover regions during the late snowmelt period (May-July). The nodes are arranged in a concentric fashion, with the innermost nodes representing aerosol predictors (highlighted with light red shading) and the outermost nodes representing meteorology predictors (highlighted with light blue shading). The interaction importances is shown through edges connections/lines between the nodes and are weighted by colors and width denoting the strength of the importance (1 to 100%, very low-low for <=25%, low-moderate for 25% to 50%, moderate-high for 50% to 75%, and high-very high for >=75% shown in the color bars).



Supplementary Figure 4. Spatio-temporal distribution of surface black carbon (BC) and dust mixing ratios (DU) over HMA. (a) Temporal average (2003-2018) of BC and DU at a horizontal resolution of 0.75º used in our methodology across three reanalysis datasets during the late snowmelt season (May - July). Blue regions denote low snow cover (LSC) regions, while red regions denote high snow cover (HSC) regions. (b) Monthly time series of BC and DU across LSC regions for the three reanalysis datasets. The width of the bars represents the interquartile range (IQR) with the median denoted by dark circles.



Supplementary Figure 5. Importance of aerosol-meteorology interactions on snow in low and high snow-covered regions. Distributions of importance metrics, relative importance (RI, solid), and Shapely contribution (SHAPc,dashed) for aerosol-meteorology (AMI) and meteorology-meteorology (MMI) interactions on snow shown for the Obs-Model (a) and Model-Model (c) construct across three reanalyses (ERA5/CAMS-EAC4, MERRA-2 and MATCHA).

Supplementary Table 1. Overview of reanalysis and observation datasets used.

	ERA5/CAMS-EAC4	MERRA-2	MATCHA
Spatial Resolution	0.1° (ERA5-Land) 0.25° (ERA5) 0.75° (CAMS-EAC4)	0.5° by 0.625°	12 km
Temporal Resolution	hourly	hourly	hourly to 3-hourly
Atmospheric Model	IFS Cy41r2	GEOS 5.12.4	WRF v3.9.1
Land Model	HTESSEL [1]	Catchment LSM [2]	CLM v4.5 – SNICAR [3]
Snow Model	1 Layer	3 Layer	5 Layers
Aerosol Model	CAMS-IFS [4]	GOCART [5]	MOSAIC [6]
Coupling Schemes	None till date [a]	Aerosol-Radiation [b]	Aerosol-Radiation-Snow [c]
Assimilated Observations			
Snow	in-situ (not for >1500 m elevation locations) IMS (4 km)		
AOD	AATSR (Envisat) MODIS Terra/Aqua	MISR AERONET MODIS Terra/Aqua	MODIS Terra/Aqua
CO	MOPITT CO (Total Column)		MOPITT CO (Profile and Total Column)

[a]Aerosol reanalysis from CAMS is not coupled to ERA5 meteorology which instead uses a monthly climatology for aerosols. Recent developments suggest a step towards incorporating aerosol coupling in the ECMWF IFS model [7].

[b]Aerosol reanalysis is radiatively coupled into the GEOS-5 model.

[c]Aerosol products are radiatively coupled with meteorology in WRF, while CLM-SNICAR couples aerosol deposition to snow properties.

Supplementary Table 2. Overview of the variables used in our study.

Reanalysis					
Predictors	**Group**	**Variable Name (with units)**	**ERA5/ERA5-L/CAMS**	**MERRA2**	**MATCHA**
	Carbonaceous	BC mixing ratio at the surface (kg/kg)	aermr09 aermr10	BCPHOLIC BCPHOBIC	BC_SFC_TOT
	Carbonaceous	OM mixing ratio at the surface (kg/kg)	aermr07 aermr08	OCPHILIC OCPHOBIC	OC_SFC_TOT
	Dust	DU mixing ratio at the surface (kg/kg)	aermr0(4-6)	DU00(1-5)	DUST_SFC_TOT
	Sulphate	SU mixing ratio at the surface (kg/kg)	aermr11	SO4	SO4_SFC_TOT
	Others	SS mixing ratio at the surface (kg/kg)	aermr0(1-3)	SS00(1-5)	NA_SFC_TOT
	Others	Aerosol optical depth at 550nm*	taod550	TOTEXTTAU	AOD_550
	Moisture	Daily Accumulated Precipitation (mm)	tp (ERA5-Land)	PRECTOTLAND	RAINC RAINNC
	Moisture	Specific Humidity (kg/kg)	d2m [a]	QV2M	Q2
	Circulation	Geopotential Height at 500 hPa (m)	z	H	PHP
	Circulation	Geopotential Height at 300 hPa (m)	z	H	PHP
	Circulation	Mean Sea Level Pressure (Pa)	msl	SLP	P PB
	Circulation	Zonal Wind at 10 m (m/s)	u10	U10M	U10
	Circulation	Meridional Wind at 10 m (m/s)	v10	V10M	V10
	Cloud Cover (CC) [b]	Total CC	tcc	CLDTOT	CFRACT

Cloud Cover (CC)	High CC [c]	hcc	CLDHGH	CFRACT
Cloud Cover (CC)	Medium CC [d]	mcc	CLDMID	CFRACT
Cloud Cover (CC)	Low CC [e]	lcc	CLDLOW	CFRACT
Temperature	Temperature at 2 m (K)	t2m	T2M	T2
Temperature	Skin Temperature (K)	skt	TS	TSK
Radiation	Surface Sensible Heat Flux (W/m2)	sshf	SHLAND	HFX
Radiation	Surface Latent Heat Flux (W/m2)	slhf	LHLAND	LH
Elevation	Elevation (m)	GMTED2010		
Target	Snow Cover Fraction (%)	sc (ERA5-Land)	FRSNO	SNOWFRAC
Observations	Snow Cover Fraction (%)	MOD10C1 MYD10C1		
	Land Surface Temperature (K)	MOD11C1 MYD11C1		
	AOD at 550 nm*	MCD19A2		
	Daily Accumulated Precipitation (mm)	IMERG Final Run		

[a]Dewpoint at 2m from ERA5 converted to specific humidity following Bolton [8].

[b]All cloud cover variables are in fraction (0-1).

[c]High cloud cover defined for model pressure levels < 0.4-0.45 P_s hPa across all three reanalyses where P_s is the surface pressure in hPa.

[d]Medium cloud cover defined with (0.4-0.8) P_s hPa for ERA5 and MATCHA, while 400-700 hPa based on MERRA-2's model terrain following coordinate.

[e]Low cloud cover defined within (1 – 0.8) P_s hPa for ERA5 and MATCHA while 1000-700 hPa based on MERRA-2's model terrain following coordinate.

*Aerosol optical depth at 550 nm is unitless.

Supplementary References

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