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A simple snow temperature index model exposes discrepancies between reanalysis snow water equivalent products

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S1 Details about reanalysis products

All three global reanalyses assimilate conventional atmospheric measurements, with ERA5 and JRA-55 additionally assimilating surface snow depth observations and satellite-derived snow extent information. In these two reanalyses, in-situ snow depth measurements are assimilated during the land surface analysis step using 2-D optimal interpolation (2D-OI) schemes. 2D-OI primarily impacts observation-dense regions and nudges the first guess field towards the observed values. In regions with few or no in-situ snow depth observations, the land surface/snow model plays a more significant role in generating the reanalysis SWE. Further, the available historical snow data tends to be biased to open terrain, low-elevations, and the mid-latitudes.(Dyer & Mote, 2006; Mortimer et al., 2020). ERA5 and JRA-55 assimilate SYNOP snow depth observations, and JRA-55 additionally assimilates station data from Russia, USA, and Mongolia.

Apart from data assimilation, differences exist in data resolution and snow model complexity. Gridded ERA5 data are at a finer resolution of 0.25°x0.25°, while JRA-55 gridded data are coarser (1.25°x1.25°), and MERRA-2 falls in between (0.5°x0.625°). The ERA5 land model allows a single layer of snow on each sub-grid scale land tile. This snow layer has a temperature, mass, density, and albedo. Terrain albedo and snow-covered fraction, which is determined based on physical snow depth (diagnosed from mass and density), are used for other calculations at the snow-atmosphere interface. In the JRA-55 land model, there can be only one snow layer with evolving SWE and temperature, but with a constant density of 200 kg m^{-3} of snow assumed [source: https://www.jma.go.jp/jma/jma-eng/jma-center/nwp/outline2007-nwp/index.htm, last accessed 22-Jan-2024]. There is no snow albedo evolution. Finally, the MERRA-2 land model allows up to three snow layers (Reichle et al., 2017b). Snow depth, snow heat content, and snow water equivalent are all modeled.

S2 Bias correction methodology

Due to the differences in temperature and precipitation forcing between reanalyses, we implement a simple bias correction to test the impact of driving data biases on resulting SWE. For a chosen dataset, monthly multiplicative scaling factors are calculated with respect to a target dataset at each grid cell. The B-TIM is then run using driving data with scaling factors applied at each time step. Our method is based on climatologies and is intended to yield matching monthly climatologies (for precipitation or temperature) between the chosen dataset and a target dataset.

For a variable X representing precipitation or 2-meter temperature, the bias corrected version would be:

$$X_b(i,j,s,m,y) = X(i,j,s,m,y) \times SF(i,j,m), \quad (10)$$

where i and j represent the spatial dimensions. The variables s, m, and y indicate sub-monthly timestep, calendar month, and year. The scaling factors, $SF(i,j,m) = \frac{\overline{X_T(i,j,m)}}{\overline{X(i,j,m)}}$, depend on location and month and X_T refers to a target dataset. The overline indicates temporal averaging over all years for a particular calendar month, m. This method preserves the pattern and number of precipitation-free days and retains the fractional interannual variability of a given dataset, all while matching it to the target monthly climatology. Swapping different target datasets X_T provides a simple way to test the effect of reduced forcing differences – in particular, if it reduces the SWE biases that result. See for example Fig. 5. Scaling factor values are bounded by 0.33 and 3 for precipitation and 0.99 and 1.01 for temperature.

Commonly, when correction factors are based on the bias between ground-truth and modeled data, normally distributed biases are corrected with an additive method, and lognormally distributed biases are corrected by multiplicative adjustment. This usually means temperature biases are corrected by adding a constant, while precipitation biases are scaled multiplicatively. This has the added benefit of maintaining the zero bound of precipitation. Given the small climatological temperature biases (no more than 2% of absolute temperature), multiplicative and additive methods yield similar results. We used a multiplicative method for both variables to simplify the experiment runs.

Table S1 Parameter values and units for model equations.

Description	Symbol	Value	Units	Equation
New snow density	A	67.9	kg m^{-3}	(1)
	B	51.3	kg m^{-3}	(1)
	C	2.6	K	(1)
Melt factor	M_1	4.08×10^{-7}	m (snow) K^{-1} hr^{-1}	(3)
	M_2	9.96×10^{-5}	mm (w.e.) K^{-1} hr^{-1}	(3)
Melt threshold	T_{melt}	-1.0	°C	(4)
Melt from rainfall	C_w	4.18×10^3	J kg^{-1} K^{-1}	(5)
	T_{freeze}	0.0	degrees C	(5)
	L_f	0.334×10^6	J kg^{-1}	(5)
	ρ_{water}	1000	kg m^{-3}	(5)
Cold densification	C_1	1.2	m^{-2}	(7a)
	C_2	0.028	m^3 kg^{-1}	(7a)
	C_3	0.08	K^{-1}	(7a)
Warm densification	W_1	204.70	mm (w.e.)	(7b)
	W_2	0.673	m	(7b)
	W_{max}	700	kg m^{-3}	(7b)
	Δt	3600	s	(7c)
	a	2.778×10^{-6}	s^{-1}	(7c)

Table S2 Variables used from each reanalysis. "T" refers to the 2-meter temperature variable and "P" refers to the total precipitation, both of which are used to drive the B-TIM. "SWE" refers to the snow water equivalent (w.e.) variable from each reanalysis.

	Reanalysis	Model Variable	Units	Frequency
T	ERA5/ERA5Snow	Parameter ID 167: "t2m"	K	1h
	JRA-55	Parameter Code 11: "TMP"	K	3h
	MERRA2	inst1_2d_asm_Nx: "T2M"	K	1h
P	ERA5/ERA5Snow	Parameter ID 288: "tp"	m/hr	1h
	JRA-55	Parameter Code 61: "TPRAT"	mm/day	3h
	MERRA-2	tavg1_2d_lnd_Nx: "PRECTOTLAND"	mm/s	1h
SWE	ERA5	Parameter ID 141: "sd"	m (w.e.)	1h
	ERA5Snow	Available on request.	m (w.e.)	1h
	JRA-55	Parameter Code 65: "SNWE"	mm (w.e.)	3h
	MERRA-2	tavg1_2d_lnd_Nx: "SNOMAS"	mm (w.e.)	1h

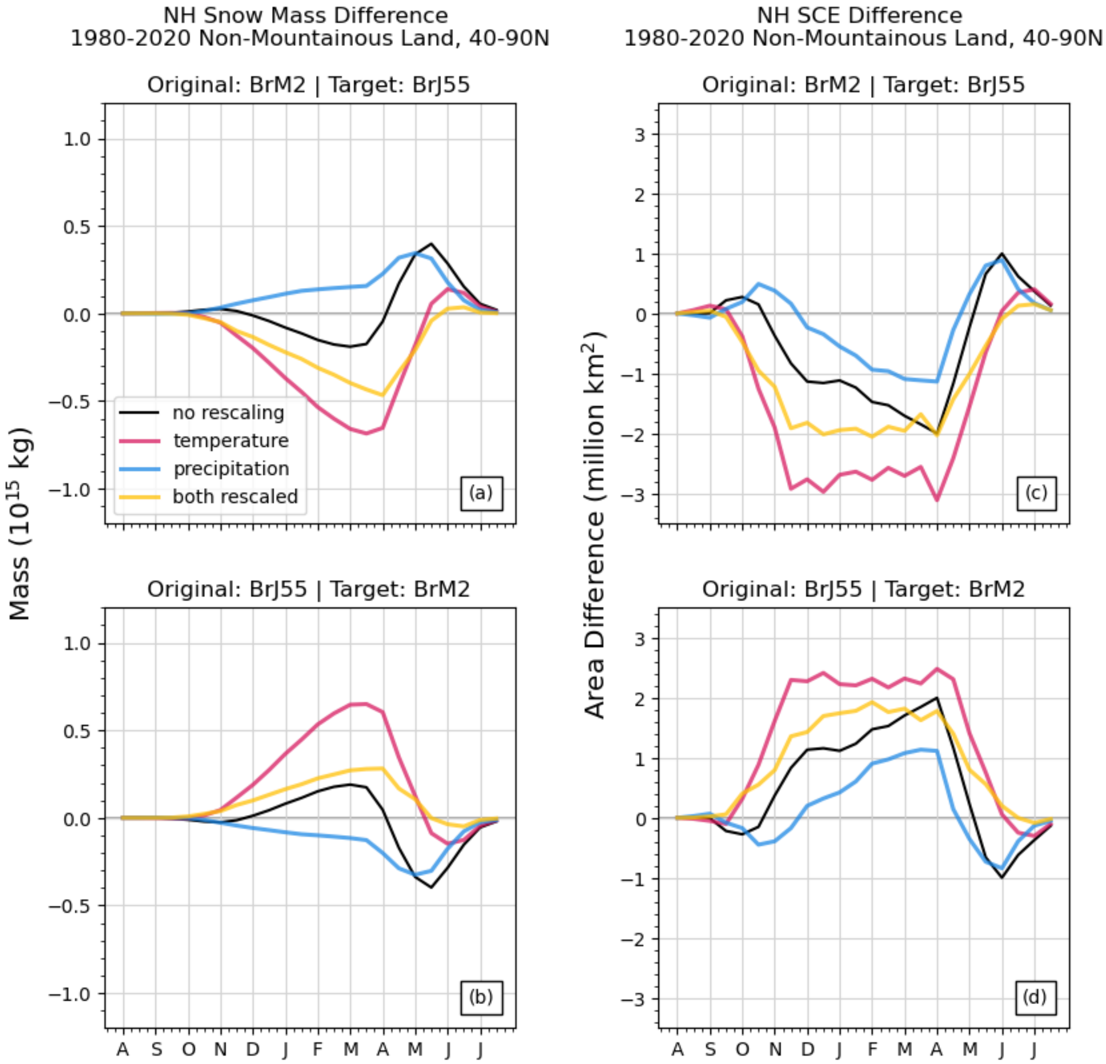
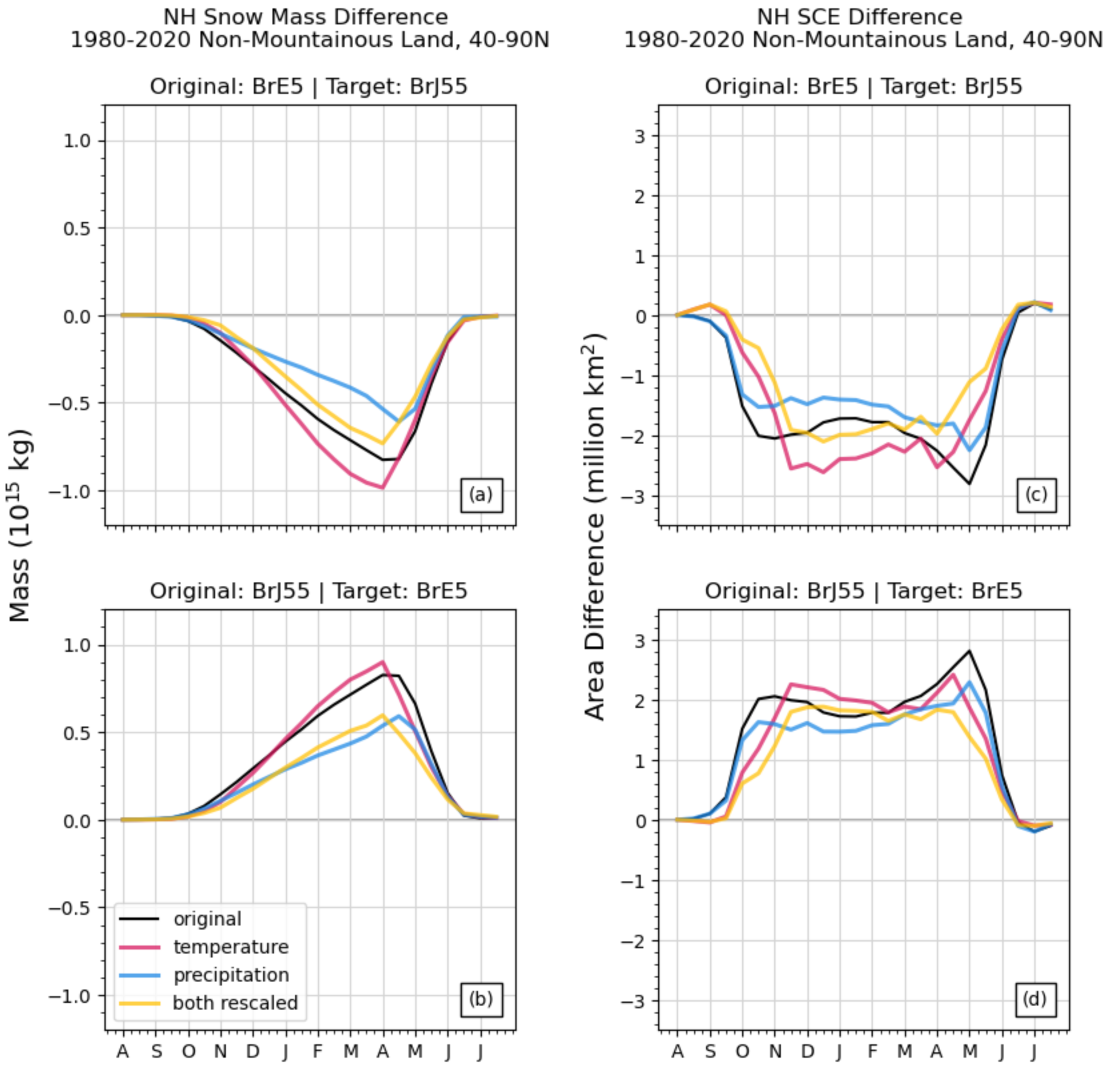


Fig. S1 Same as Fig. 5 for MERRA-2 and JRA-55. (a,b) NH snow mass and (c, d) snow cover extent differences calculated as original minus target. Each panel shows the difference between the original and target snow mass climatologies (black) and the coloured lines represent the versions resulting from adjusting temperature (pink), precipitation (blue), or both (yellow) to the target dataset's climatology.



65 **Fig. S2 Same as Fig. 5 for ERA5 and JRA-55. (a,b) NH snow mass and (c, d) snow cover extent differences calculated as original minus target. Each panel shows the difference between the original and target snow mass climatologies (black) and the coloured lines represent the versions resulting from adjusting temperature (pink), precipitation (blue), or both (yellow) to the target dataset's climatology.**

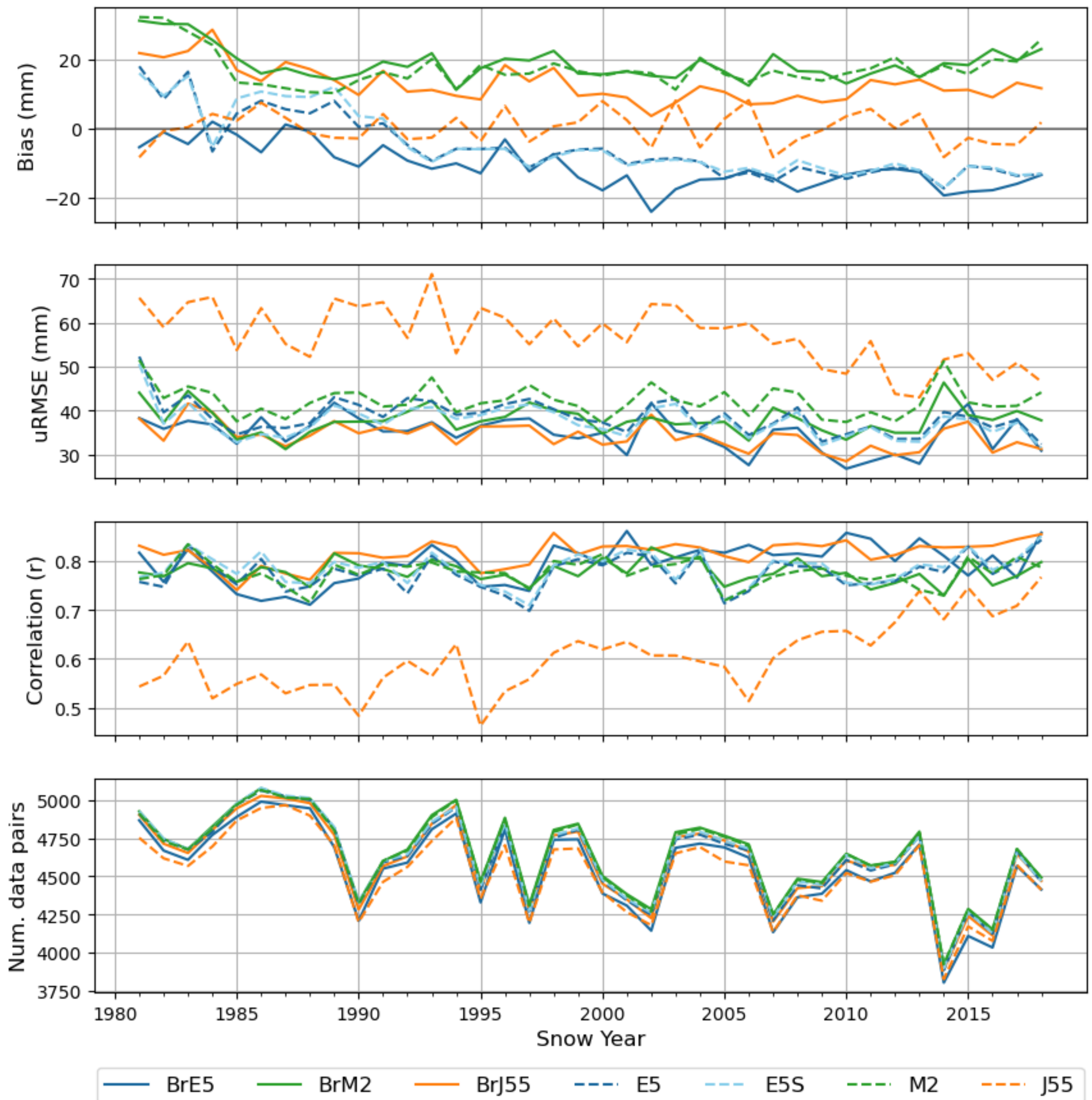


Fig. S3 Time series of validation metrics. DJF measurements for 1980-2018. Dashed lines are reanalysis SWE (ERA5, ERA5Sow, MERRA2, and JRA-55), while solid are B-TIM outputs (BrE5, BrM2, BrJ55).

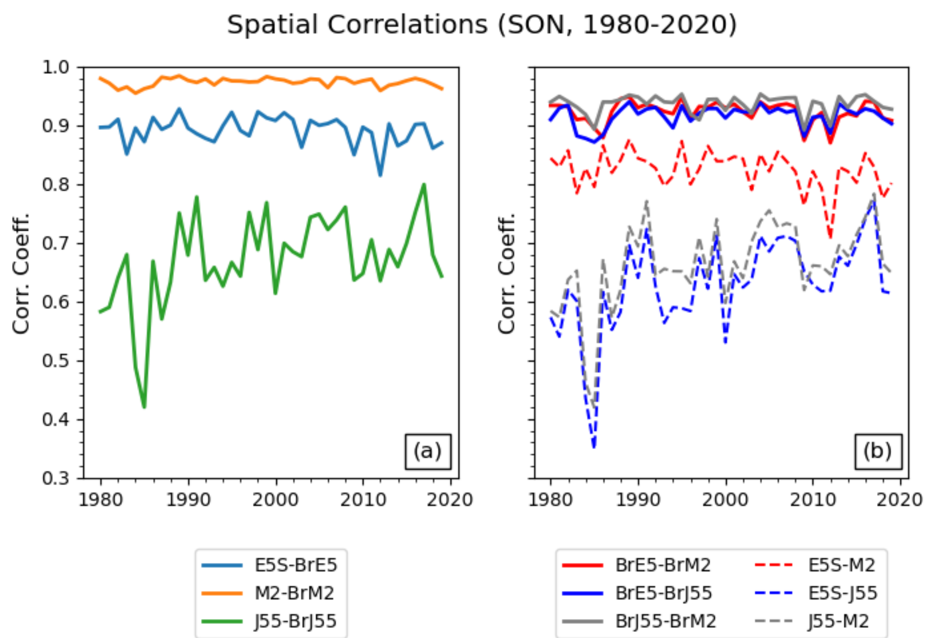


Fig. S4 Spatial correlations for SON calculated between pairs of datasets with the same meteorology (a) and between pairs of similar type (b; either offline-offline or reanalysis-reanalysis).

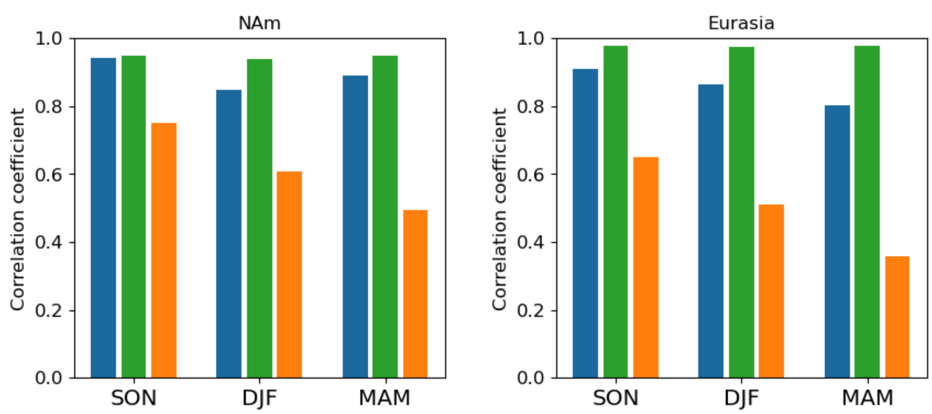


Fig. S5 Spatial correlations for SON, DJF, MAM for reanalysis-offline (same forcing) pairs. BrE5-ERA5 pair in blue, BrM2-MERRA2 pair in green, and BrJ55-JRA55 pair in orange. Values are split for two continents.