Interactive comments on "Space-time variability of soil moisture droughts in the Himalayan region"

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Anonymous Referee #3

We are very grateful to the reviewer #3 for providing valuable comments to our paper. We have greatly benefited from these comments. We hereby provide a detailed response to these comments:

The reviewer comment is marked as **[Comment]** and our response immediately as **[Response]** (in blue font) and part of the revision in the manuscript in *italics.*

[Comment]
The approach is standard and the comparison with observations is limited to temporal scale, whilst spatial scale is widely discussed.

[Response]
Thank you for bringing this important point about the spatial maps. Now we have included spatial maps to show the average SMDI and duration of drought events:

We have discussed the magnitude of 'drought' events (i.e. SMDI values lower than -3.0). Now we have included spatial drought maps in two places. Figure 8 shows the average spatial SMDI maps including the driest and wettest year. Similarly, Figure 11 shows the duration of drought events (i.e. SMDI below -3.0), including the driest and wettest year. To complement this figure, we also calculated average SMDI values and duration of drought events for 3 physiographic region and whole basin for each year (Table 3 and Table 4), and also discussed these aspects in results and discussion section.

The new addition of spatial maps and tables are provided below:

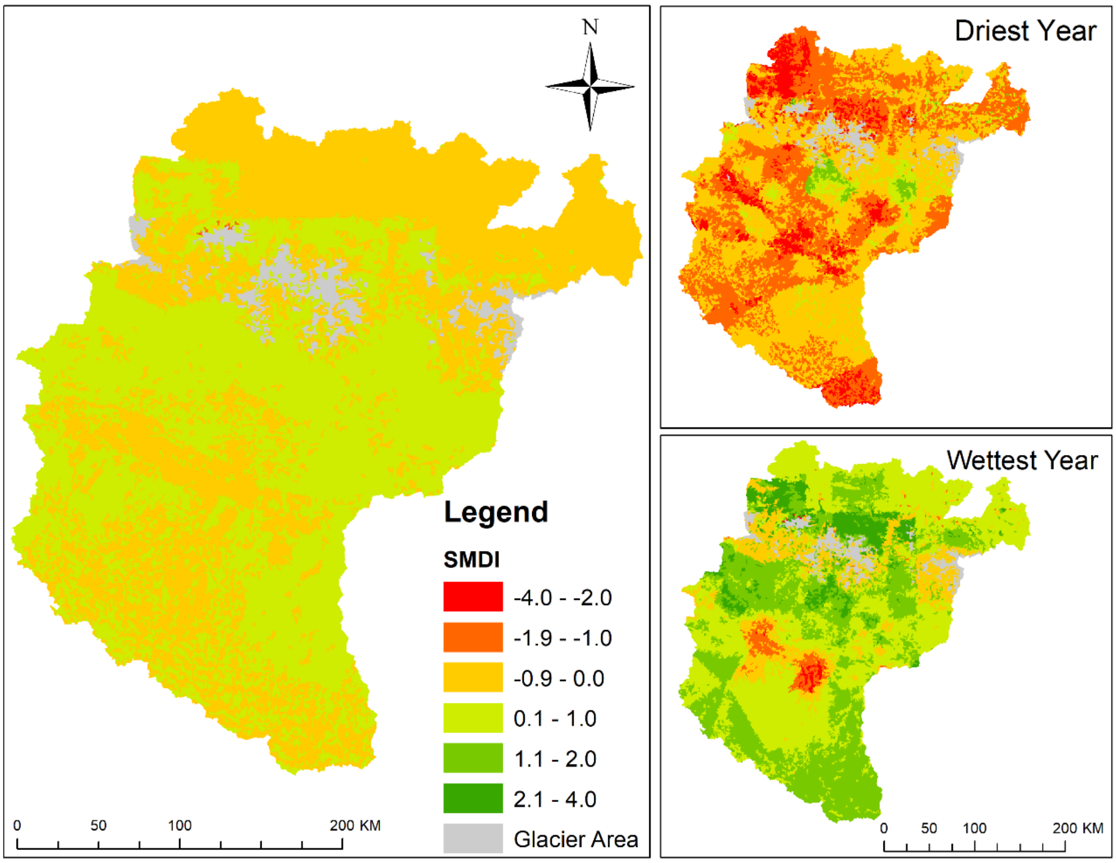

Figure 8: Spatial maps of average annual SMDI (1980-2007), dryest year (1992) and wettest year (1998).

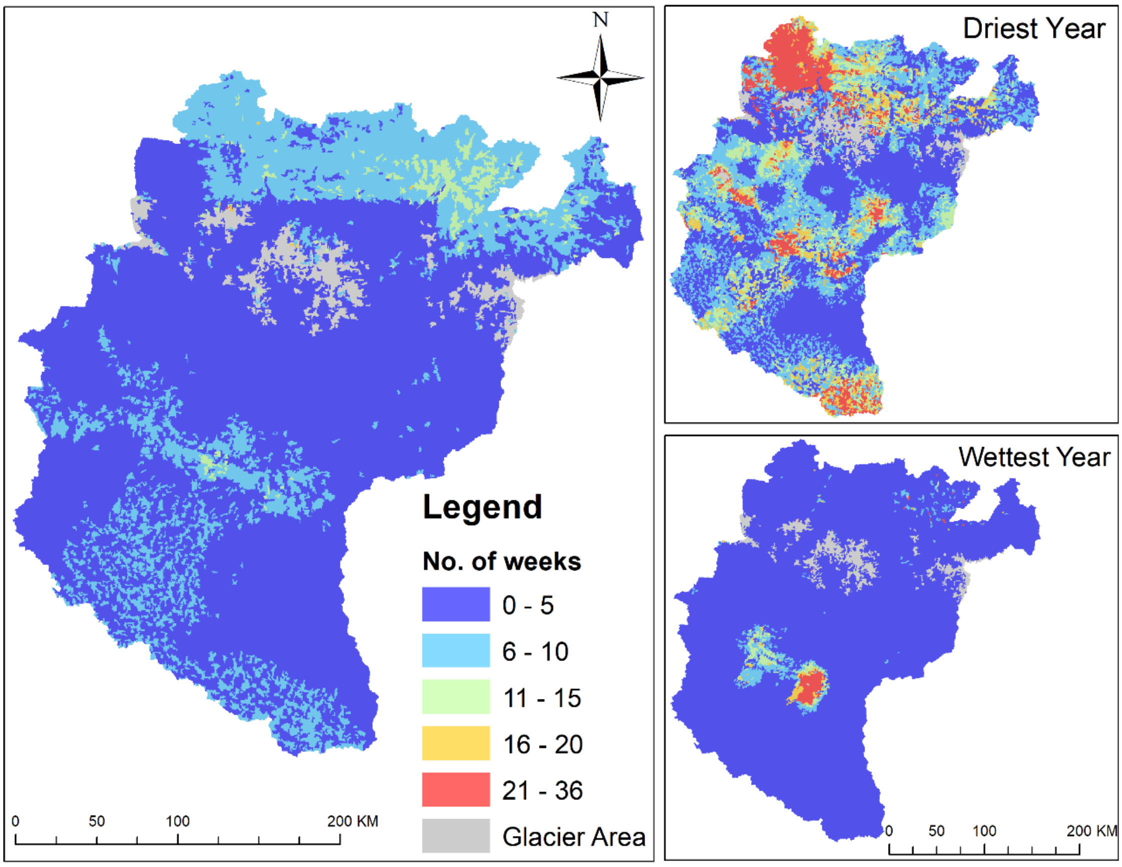

Figure 11: Spatial maps of average duration of drought i.e. SMDI < -3.0, dryest year (1992) and wettest year (1998).

Table 3: Average annual SMDI values from 1980-2007 for Trans-Himalaya, Mountains and Plains and for the whole Koshi basin. The red bar shows the negative and blue shows the positive SMDI values, the average SMDI values for each year are given in the respective rows.

Year	Trans-Himalaya	Mountains	Plains	Koshi Basin
1980	1.49	0.21	0.57	0.72
1981	1.26	-0.20	0.28	0.4
1982	-0.66	-0.23	-0.32	-0.39
1983	-1.21	0.45	-0.04	-0.21
1984	-0.45	0.07	0.31	-0.02
1985	-0.39	0.15	0.51	0.09
1986	-0.29	0.96	0.18	0.33
1987	-0.33	0.55	0.65	0.31
1988	0.35	0.09	0.11	0.18
1989	-0.29	0.04	-0.17	-0.13
1990	-0.50	0.35	0.01	-0.02
1991	-0.49	-0.57	-0.42	-0.5
1992	-1.08	-0.78	-0.91	-0.91
1993	-0.24	0.34	-0.24	-0.02
1994	-1.11	-0.31	-0.97	-0.76
1995	-1.00	-0.30	-0.98	-0.72
1996	1.06	0.41	-0.01	0.49
1997	0.12	0.00	-0.17	-0.02
1998	0.92	0.71	0.87	0.82
1999	1.18	-0.11	0.36	0.43
2000	1.29	0.00	0.22	0.47
2001	-0.84	-0.09	-0.28	-0.38
2002	-1.23	0.35	0.41	-0.12
2003	-0.79	0.25	1.01	0.16
2004	-0.87	0.43	0.24	-0.03
2005	-1.05	-0.23	-0.72	-0.63
2006	-1.35	-0.26	-0.41	-0.64
2007	-0.28	0.62	0.39	0.27

Table 4: Duration of drought events for trans-Himalaya, Mountains and Plains and for the whole Koshi basin. The red bars corresponding to values on the rows show the number of weeks where SMDI < -3.0.

Year	Trans-Himalaya	Mountains	Plains	Koshi Basin
1980	0.3	3.3	2.1	2.0
1981	0.4	4.3	1.4	2.2
1982	10.6	3.7	3.3	5.7
1983	11.5	2.2	5.1	6.0
1984	5.0	2.6	2.8	3.4
1985	3.2	2.4	2.9	2.8
1986	4.1	0.7	1.4	2.0
1987	5.7	1.1	1.8	2.7
1988	0.7	1.7	2.9	1.8
1989	1.7	3.7	4.0	3.2
1990	3.1	1.3	1.3	1.8
1991	4.7	5.4	5.8	5.3
1992	11.1	7.6	7.1	8.5
1993	1.4	1.5	4.6	2.4
1994	5.0	4.0	8.5	5.7
1995	7.2	5.0	12.8	8.0
1996	0.9	2.2	5.7	2.9
1997	1.2	2.4	1.7	1.8
1998	1.0	1.3	1.4	1.2
1999	0.3	4.9	2.5	2.8
2000	0.3	2.0	2.7	1.7
2001	6.9	3.3	3.3	4.4
2002	10.4	0.9	0.9	3.8
2003	5.5	1.9	1.4	2.9
2004	6.2	1.6	1.6	3.0
2005	6.8	3.8	5.6	5.3
2006	13.9	4.7	4.2	7.4
2007	7.8	1.3	1.9	3.5

[Comment]
The authors are asked to give an information on the number of parameters that needed to be set in the model and a number of parameters that were calibrated.

[Response]
The table of the model parameters and their range are provided in supplementary table 3

Supplementary Table 1: Calibration parameters in the J2000 hydrological model.

Note: the parameters (in bold) were the 16 selected parameters for sensitivity and uncertainty analysis by Nepal et al. (2017).

Parameter	Description	Calibrated value	Normal range	Units
Precipitation distribution				
Trs	Base temperature	0	−1 to +1	°C
Trans	Parameter range for mixed rain and snow	2	−2 to +2	°C
Interception module				
a_rain	Interception storage for rain	1	0–5	mm
a_snow	Interception storage for snow	1.28	0–5	mm
Snow module				
CritDens	Critical density of snow	0.381	0–1	%
ColdContent	Cold content of snowpack	0.0012	0–1	NA
BaseTemp	Threshold temperature for snowmelt	0	−5 to +5	°C
Tfactor	Melt factor by sensible heat	2.84	0–5	NA
Rfactor	Melt factor by liquid precipitation	0.21	0–5	NA
Gfactor	Melt factor by soil heat flow	3.73	0–5	NA
Glacier module				
meltFactorIce	Melt factor for ice melt	0.5	0–5	NA
alphaIce	Radiation melt factor for ice	0.1	0–5	NA
kIce	Routing coefficient for ice melt	15	0–50	NA
kSnow	Routing coefficient for snowmelt	10	0–50	NA
kRain	Routing coefficient for rainfall–run-off	5	0–50	NA
debrisFactor	Debris factor for ice melt	5	0–10	NA
glacierTbase	Threshold temperature for snowmelt	−1	−5 to +5	°C

Soil module				
soilMaxDPS	Maximum depression storage	2	0–10	mm
soilLinRed	Linear reduction coefficient for actual evaporation	0.6	0–1	
soilMaxInfSummer	Maximum infiltration in summer	45	0–200	mm
soilMaxInfWinter	Maximum infiltration in winter	50	0–200	mm
soilMaxInfSnow	Maximum infiltration in snow-covered areas	40	0–200	mm
soilInpLT80	Infiltration for areas less than 80% sealing	0.5	0–1	NA
SoilDistMPSLPS	MPS–LPS distribution coefficient	0.27	0–10	NA
SoilDiffMPSLPS	MPS–LPS diffusion coefficient	0.1	0–10	NA
soilOutLPS	Outflow coefficient for LPS	7	0–10	NA
soilLatVertLPS	Lateral vertical distribution coefficient	0.05	0–10	NA
soilMaxPerc	Maximum percolation rate to groundwater	30	0–100	mm
soilConcRD1Flood	Recession coefficient for flood event	1.1	1–10	NA
soilConcRD1Flood threshold	Threshold value for soilConcRD1Flood	500	0–500	NA
soilConcRD1	Recession coefficient for overland flow	1.5	1–10	NA
SoilConcRD2	Recession coefficient for interflow	1.8	1–10	NA
Groundwater module				
gwRG1RG2dist	RG1–RG2 distribution coefficient	20	0–5	NA
gwRG1Fact	Adaptation factor for RG1 flow	0.05	0–10	NA
gwRG2Fact	Adaptation factor for RG2 flow	0.18	0–10	NA
gwCapRise	Capillary rise coefficient	0.01	0–10	NA
Reach routing				
flowRouteTA	Flood routing coefficient	30	0–100	NA

[Comment]

A discussion on data quality and uncertainty of the model results should be provided.

[Response]

A new paragraph is added describing the uncertainty and limitations of data quality and availability in the Discussion section. The data description is provided in Supplementary Table 1.

The new paragraph in the discussion section reads as:

Uncertainties and limitations

The model results are subject to several uncertainties and limitation which are briefly described below. The calibration and validation of hydrological model results are subject to uncertainty arising from model input data, parameter and structural uncertainty. In the mountainous region, the representation of the observed station network is sparse and limited which is the case in the KRB. For the northern part of China and southern Indian side, gridded datasets were used compared to station data in the Southern Himalaya in Nepal part. The application of APHRODITE data in the northern region has limited the study period up to 2007 because of the data available only up to this period. The station data are mostly limited to the lower elevation areas with limited station network in high altitude areas. Both the gridded and observation network have their advantage and disadvantages for modelling applications. Nonetheless, our approach of using both gridded and station data along with discharge data have enabled us to use the modelling period of 28 years which is a relatively a longer period in the case of transboundary KRB.

Regarding the parameter uncertainty, the application of the J2000 hydrological model in the previous studies has shown the potential of spatial transferability of model parameters within the sub-catchments of the Koshi basin (Nepal et al. 2017). The generalised likelihood uncertainty estimation (GLUE) analysis of two sub-catchments of the Koshi basin suggests that most of the time the parameter uncertainty can be explained within the ensemble range of multiple simulations, except some flood events. Supplementary Table 2 shows the J2000 model parameters including the selected parameters which were used for sensitivity and uncertainty analysis by Nepal et al. (2017). Similarly, there were good matches on the category of high, moderate and low sensitive parameters between the two catchments suggesting the robustness of the model in the Himalayan catchments. The results have also suggested that spatial transferability of model parameters in the neighbouring catchment with similar climatic and hydrological conditions are possible in the Himalayan region (Nepal et al, 2017), however, some variation is parameters can be expected if the scale of the basin size and climatic conditions differ (Eeckman et al. 2019; Shrestha and Nepal, 2019). Besides, the soil moisture from the J2000 model was not validated independently due to the lack of the observed data and validation was only limited to discharge and evaporation data. Despite these uncertainties and limitation, the model has replicated overall hydrological behaviour including both low and high flows, similar to the previous studies in the Koshi basin (Nepal et al. 2014, Nepal et al, 2017; Eeckman et al. 2019).

Supplementary Table 3: List and sources for the spatial and climatic datasets used in the J2000 Model for the Koshi River Basin

SN	Data	Data Sources
1	Digital Elevation Model (DEM)	ASTER GDEM
2	Land use map	Uddin et al. (2016)
3	Soil map	SOTER
4	Geology map	DMG (1994)
5	Meteorological data (stations numbers)	
	i. Precipitation (160)	DHM[a], IMD[b], APHRODITE[c]
	ii. Temperature (60)	DHM, IMD, CFSR[d]
	iii. Relative humidity (73)	DHM, IMD, CFSR
	iv. Wind (66)	DHM, IMD, CFSR
	v. Sunshine hours (4)	DHM

Notes:

1: ASTER GDEM: Advanced Spaceborne Thermal Emission and Reflection Radiometer. https://asterweb.jpl.nasa.gov/gdem.asp

2: Uddin et al. (2016) http://rds.icimod.org/Home/DataDetail?metadataId=9224

3: SOTER: Soil and Terrain Databases, Food and Agriculture Organization of the United Nations (FAO). http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/regional-and-national-soil-maps-and-databases/en/

4: DMG, Department of Mines and Geology, Nepal (based on physiographic division of Nepal)

5 a,b,c,d,e : DHM: Department of Hydrology and Meteorology, Nepal.

5 a,b,c,d : IMD: Indian Meteorological Department, India.

5 c: APHRODITE: Asian Precipitation – Highly-Resolved Observational Data Integration Towards Evaluation of Water Resources. (V1101) http://www.chikyu.ac.jp/precip/english/

5 b,c,d : CFSR: Climate Forecast System Reanalysis https://climatedataguide.ucar.edu/climate-data/climate-forecast-system-reanalysis-cfsr

[Comment]
The discussion also should be extended by a presentation of spatial variability of the resulting soil moisture deficit patterns and their comparison with the SPI and, additionally, SPEI indices for different sub-regions and specific time periods.

[Response]

Thank you for the important comment on the spatial maps of SMDI. We have now added the spatial maps showing the variation in SMDI and duration of drought events. The maps are posted above in relation to the first comment. The discussion of spatial maps is also included in the results and discussion section.

The main focus of the paper is to understand the soil moisture variability using SMDI index. Additionally, we calculated SPI as a meteorological drought index to see how it differs from soil moisture variability. Besides, we believe that since SPEI also uses precipitation, evaporation and temperature data, the response of SPEI and SMDI might be similar. Comparison of different drought indices would require a huge effort.

The SMDI and SPI comparison are discussed in detail in the 'Discussion' section. The related paragraph reads as:

Analysis related to SMDI and SPI, the former is able to reflect variations in soil moisture conditions better than SPI which shows normal conditions. As shown in trans-Himalaya, the period after 2001 when SPI shows wetness and SMDI show dryness during the pre-monsoon. It is because SMDI incorporates additional variables (temperature, evaporation, vegetation, root depth, and soil water holding capacities) to calculate soil moisture variability compared to only precipitation variables by SPI. As expected, the SPI gives a more homogeneous response because of the lack of the representation of physiographic differences. An example of this behaviour can be seen in winter 2006 where SPI indicates a severe drought in over 80 % of the area of trans-Himalaya and mountains (Figure 9). In contrast, SMDI shows a more differentiated pattern (Figure 8) where during winter drought conditions are indicated for roughly half of the area with severe values only for 10 to 20% of the area. Most likely, one reason for this more differentiated picture is the consideration of soil water storage in the SMDI. The remaining soil water after the post-monsoon can be very important for the water supply and overshadow the effect of (missing) precipitation in winter. Additionally, this effect can be amplified by the low ET volumes during winter (Figure 3) that deplete the stored soil moisture only slowly, resulting in higher SMDI values. The shown differences in the SMDI are caused by varying soil water storage capacities which control the duration of periods during which higher SMDI can be maintained without precipitation. The years for which both SPI and SMDI show matching drought conditions can be mainly attributed to them being the lowest rainfall periods (Figure 5).

Specific comments:

Line 301-302: sentence starting with Due to lack of consistency : : : is not necessary here (message repeated further down)

Removed

Line 352 should be: Supplementary Figure 1

The supplementary figure numbers are corrected now:

Supplementary Figure 1: Conceptual layout of the J2000 hydrological model

Supplementary Figure 2: Variation in weekly soil moisture for the Koshi River basin, 1980–2007

Line 437: Figure number is missing

Corrected

Figs 8-10 are not easy to read. It is a pity, as a comparison of those figures gives the answer to the research questions

Response:

We have now revised the figure suitable for the journal format. I think it can be read easily now. Please find the figures below:

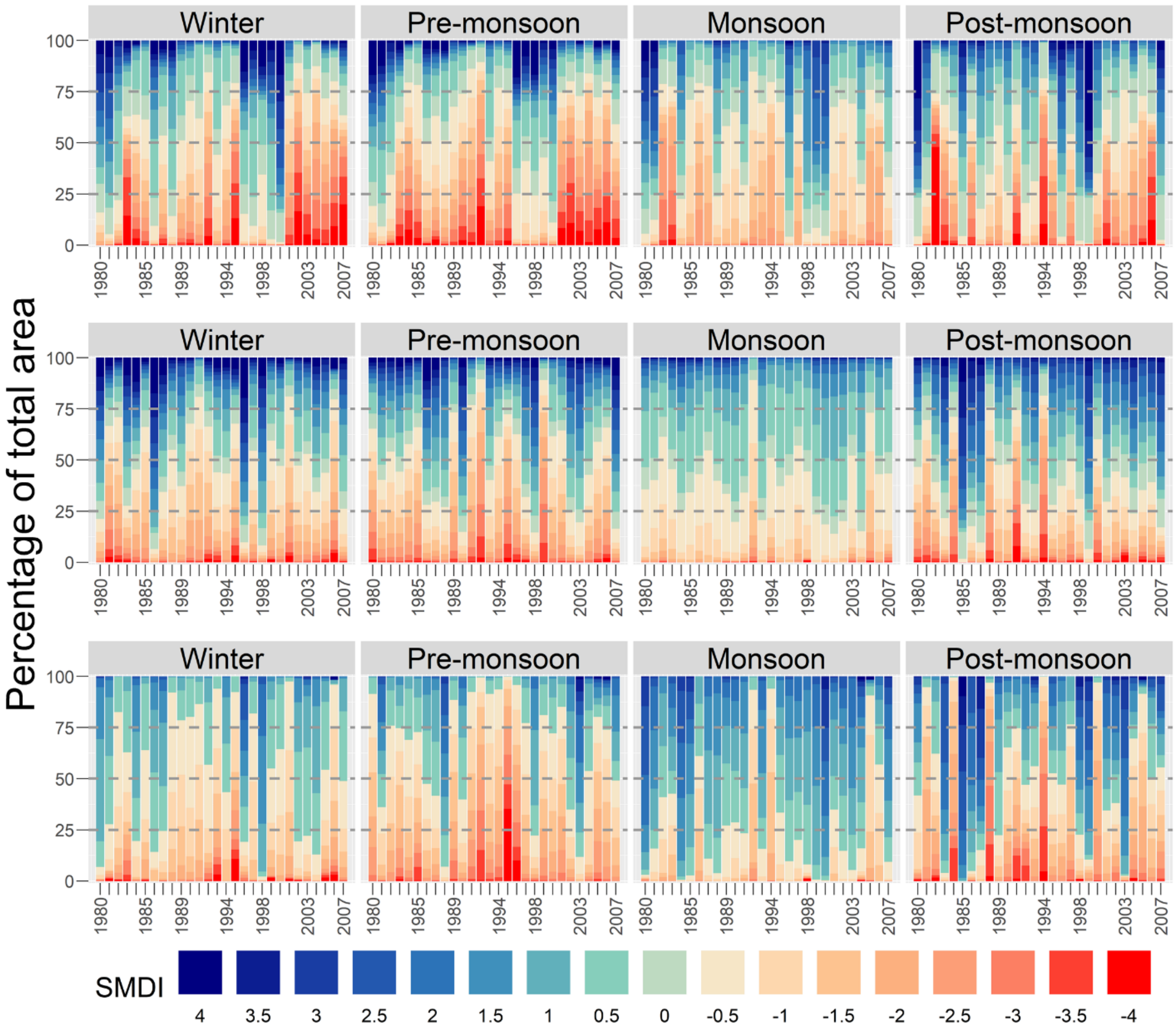

Figure 9 Spatial and seasonal variability of the SMDI in trans-Himalaya (top), the mountains (middle), and the plains (bottom)
Note: Each colour band shows the respective HRU's area combined.

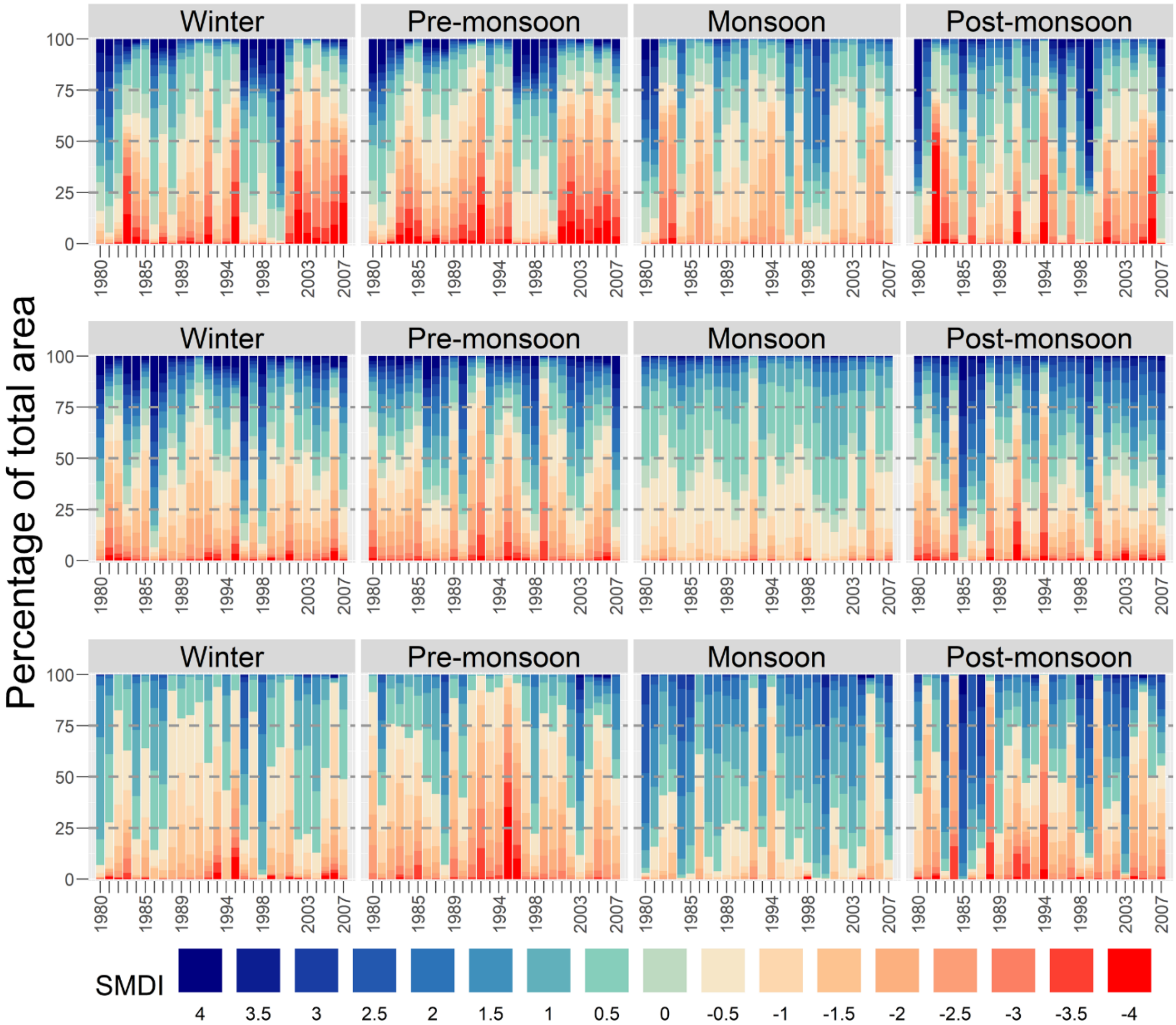

Figure 10 Spatial and seasonal variability of the SPI in the trans-Himalaya (top), the mountains (middle), and the plains (bottom)

Note: Each colour band shows the respective HRU’s area combined.

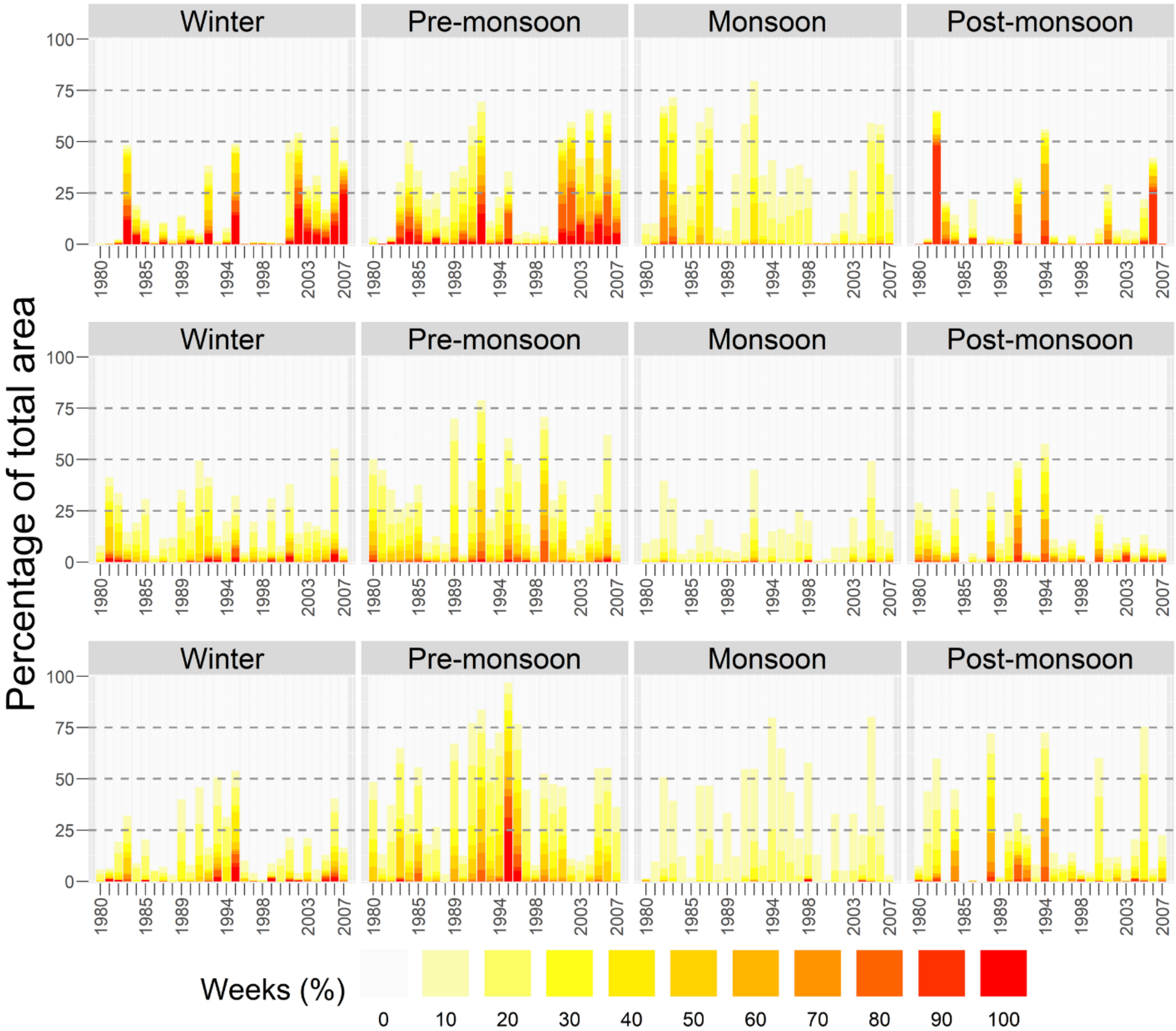

Figure 12: Percentage of weeks with severe drought in the trans-Himalaya (top), the mountains (middle), and the plains (bottom)
Note: Each colour band shows the respective HRU's area combined