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

Santosh Nepal et al.

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Anonymous Referee #1

We are very grateful to the reviewer #1 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.*

General comments

[Comment] Several indices have been developed so far to investigate agricultural droughts (see, for instance, https://nhess.copernicus.org/articles/20/471/2020/nhess-20-471-2020.pdf and references therein). In the introduction, the paper would benefit from a discussion on why SMDI has been preferred to other indices.

[Response]

We have elaborated the benefit of SMDI over other indices. We also referred to *Monteleone et al. 2020 in the introduction.*

The revised paragraph in the introduction reads as (the yellow highlights are added text):

There are many drought indices, such as the Standardized Precipitation Index (SPI), Standardized Precipitation Evaporation Index (SPEI), Evapotranspiration Deficit Index (ETDI), Soil Moisture Deficit Index (SMDI), Aggregate Drought Index (ADI), Standardized Runoff Index (SRI), Probabilistic Precipitation Vegetation Index (PPVI) and Palmer Drought Severity Index (PDSI), which indicates the differential nature of droughts that might occur at different time intervals and lag times (Bayissa et al., 2018; Huang et al., 2015; Narasimhan and Srinivasan 2005; Monteleone et al. 2020). Focusing on soil moisture variability, *SMDI takes into account more variables (such as evapotranspiration, soil properties, and root depth) than SPI and SPEI, which takes into account precipitation, and precipitation & evapotranspiration, respectively.* Therefore, *SMDI can provide dependable information to interpret the occurrence and severity of the agricultural drought. Similarly, SPI is a widely used index to characterise meteorological droughts on a range of timescales. Monteleone et al. (2020) suggested list of indices for agriculture drought monitoring, including Evapotranspiration Deficit Index (ETDI), Normalized Difference Vegetation Index (NDVI), Soil Moisture Anomaly Index (SMAI), SPI, SMDI and Standardized Soil Moisture Index (SSI). Each of these indices has their own pros and cons for different climatic variables they use for drought calculation, data requirement and availability and their potential use for agricultural drought monitoring.*

This paper aims at assessing soil moisture droughts in the Koshi River Basin. To understand soil moisture droughts, this paper considered the Soil Moisture Deficit Index (SMDI) and Standardised Precipitation Index (SPI) for 28 years (1980–2007). For soil moisture variability, SMDI takes into account precipitation, temperature, evaporation, soil and vegetation properties affecting soil moisture conditions. For this purpose, the basin's soil moisture was simulated with the use of the process-based J2000 hydrological model, which was validated against observed discharge and evapotranspiration. The J2000 model has been successfully used to investigate hydrological droughts in Central Vietnam (Firoz et al., 2018; Nauditt et al., 2017). This paper specifically investigates the spatial and temporal variability of soil moisture for the trans-Himalaya (Tibet), the high and middle mountains (Nepal), and the southern plains of the river basin (in Nepal and India). We also compared the SMDI with the SPI to identify the variation of the drought indication in space and time. SPI is a widely used index to characterise meteorological droughts on a range of timescales. To the best of our knowledge, soil moisture drought is being studied for the first time in the transboundary Koshi River basin and this paper provides insights into its spatio-temporal variability in the historic time period under consideration.

[Comment]

SMDI is calculated on a weekly basis in Equation (1). The authors should clarify how the SMDI values can be calculated on a seasonal basis.

[Response]

We have revised the paragraph in the method section to elaborate on this aspect.

The revised paragraph in the method section reads as:

The calculation of the SMDI has been implemented in the JAMS modelling system using two individual JAMS components, namely SMDI_DataCollect and SMDI_Calc. The first component is used to collect soil moisture data for each HRU during the normal hydrological simulation with J2000. In addition, this component also calculates long-term soil water statistics for each HRU (for example, MSW_w). Once this is finished, the second component (SMDI_Calc) will calculate the SMDI values for each HRU based on their weekly soil moisture values ($SW_{y,w}$) and long-term statistics (MSW_w, $minSW_w$, $maxSW_w$). While weekly intervals are used as the default, the component can calculate SMDI values based on any given aggregation period, for example, to consider individual characteristics of specific vegetation types. As described above, the HRUs were segregated into three geographical regions, trans-Himalaya, mountains, and plains, as the climatic conditions are different in each of these zones. Similarly, the SMDI values were analysed separately for four seasons: monsoon (June–September), post-monsoon (October–November), winter (December–February), and pre-monsoon (March–May). Since these seasons are defined based on variations in precipitation and temperature, the SMDI is calculated for these seasons to track the variation caused by these meteorological drivers. For this, we averaged the weekly SMDI values for a given season. In this way, the dominating climatic characteristics are maintained at the seasonal level.

[Comment]

According to LL 294-296, SPI values are computed on the same seasonal scale of SMDI (i.e. winter, DJF, pre-monsoon, MAM, monsoon, JJAS, and post-monsoon, ON). However, SPI affecting soil moisture can be related to different aggregation periods. A sensitivity analysis could help to identify the appropriate aggregation period for a better comparison with SMDI.

[Response]

We agree with the reviewer that SPI affecting soil moisture can be related to different aggregation periods. In our paper, our aim was not to correlate the aggregation period for SPI and SMDI. The focus of the paper was to look at soil moisture variability and also if SPI was able to explain that variability. The aim of using SPI was rather to show that variation in drought indication by SPI (which considers precipitation only) and SMDI (which considers more variables than precipitation, such as temperature, evaporation, soil and vegetation conditions) at the seasonal scales. Here, the seasonal aggregation is more logical because of the four dominating and distinct seasons in the KRB based on precipitation and temperature condition. Therefore, a sensitivity analysis to identify the appropriate aggregation period is out of the scope of this study.

We also clarified the SPI and SMDI aggregation period in the method section 3.3.3, which reads as:

The Standardized Precipitation Index (SPI) is the most commonly used indicator for detecting and characterising meteorological drought on different timescales. We calculated the seasonal SPI which was implemented as a JAMS component. The SPI is calculated based on a long-time series of precipitation data. The SPI measures precipitation anomalies based on a comparison of observed total precipitation amounts for an accumulation period (for example, 1, 3, 12, or 48 months) with the long-term historic record for that period. The probability distribution of the historic record was fitted to a gamma distribution, which was then transferred to a normal distribution to get a mean SPI value of zero (McKee et al., 1993; McKee et al., 1995). To compare the seasonal SMDI with the SPI, we calculated the SPI data for the same period of four seasons used to calculate the SMDI. For this, the aggregation period was based on the end month of each season and SPI accumulation period was chosen based on the months. For winter, 3 months SPI was calculated for the month of February; for pre-monsoon, 3 months SPI for May; for monsoon, 4 months SPI for September and for post-monsoon, 2 months SPI for November. In this manner, the occurrence of drought based on the SPI and SMDI in different time intervals was discussed together.

[Technical comments]

L18: something is missing after “actual”.
Corrected:
The revised sentence reads as:

In order to identify drought conditions based on the simulated soil moisture, the Soil Moisture Deficit Index (SMDI) was then calculated, considering the derivation of actual soil moisture long-term soil moisture on a weekly timescale.

L36: delete “and” after “hazards”.
Corrected:

The revised sentence reads as:

Droughts are considered one of the world’s major social and economic hazards, which have been increasing in recent decades.

LL 114-115: "SPI is a widely used index : : :" moves this sentence before in the introduction.

We moved the sentence before the introduction:

LL 351-352: There is a repetition in these lines.

The repeated lines are deleted.

Figures 8 and 9: place the panels vertically rather than horizontally.

The panels are replaced. Please see below the revised maps arranged vertically with new figure numbers

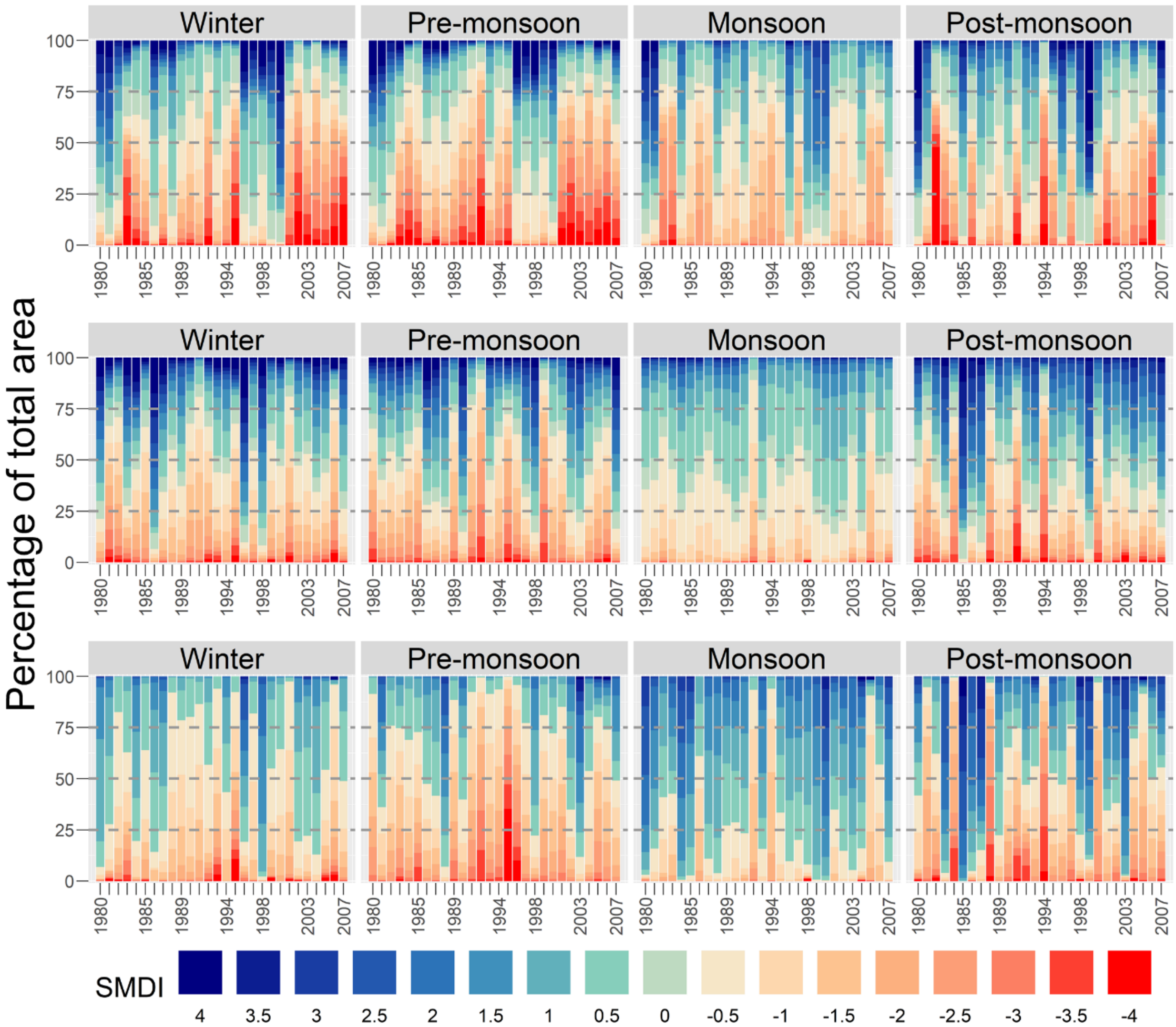

Figure 9 Spatial and seasonal variability of the SMDI in trans-Himalaya (top), the mountains (middle), and the plains (bottom)
Note: Each colour band shows the respective HRU's area combined.

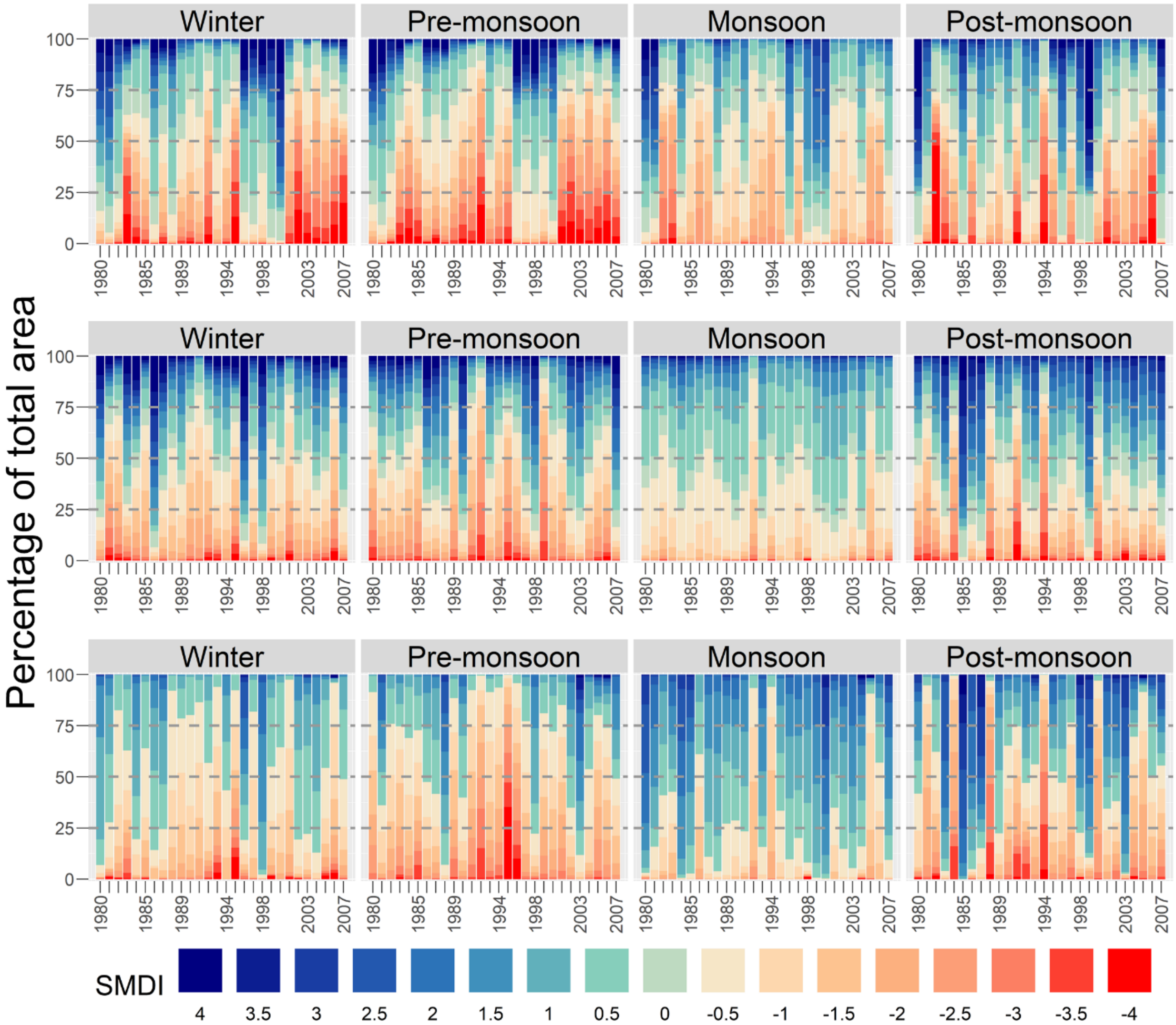

Figure 10 Spatial and seasonal variability of the SPI in the trans-Himalaya (top), the mountains (middle), and the plains (bottom)

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

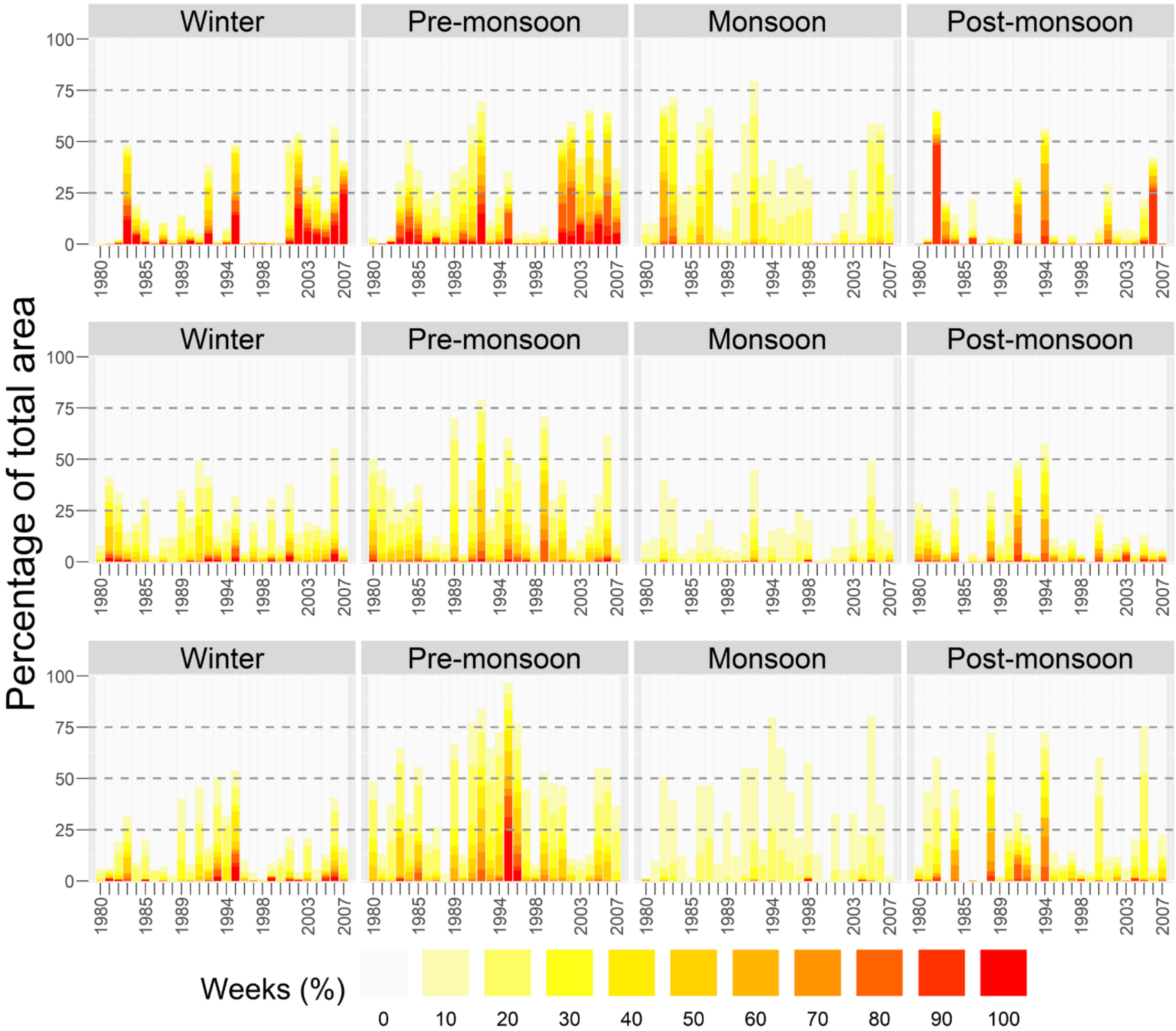

Figure 12: Percentage of weeks with severe drought in the trans-Himalaya (top), mountains (middle), and plains (bottom)
Note: Each colour band shows the respective HRU's area combined

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

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Anonymous Referee #2

We are very grateful to the reviewer #2 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 data length is 1980-2007, why the data after 2008 were not used.

[Response]
We used the APHRODITE datasets in the data-scarce region of the northern part of the Koshi basin in combination with other datasets. APHRODITE data (version: V1101) is only available up to 2007. Because of this reason, we limited the analysis period up to 2007 (i.e. 1980-2007: 28 years analysis period, 1979 as warm up year).

We have revised the paragraph to clarify the data limitation in uncertainty section in Discussion.

Uncertainties and limitations

The model results are subject to several uncertainties and limitations 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 generalized 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 3 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).*

[Comment]
The model simulated soil moisture was applied to identify soil moisture drought, but does the simulated soil moisture reflect the real soil moisture? Although the hydrological model had a good performance, if there is irrigated area in the study area, does the model consider this condition?

[Response]
Our model has not considered irrigation systems. We have validated our results with discharge and evaporation data. Due to the lack of soil moisture data in the study area, we could not validate the simulated soil moisture directly . Therefore we have assumed that as the multi-response outcomes (Q and ET) from the model have been validated, simulated soil moisture should be a good representation of the basin response. We have made this limitation clear in the method section in the revised version now.

The revised sentence in the method section (last paragraph) reads as:

Overall, the soil moisture conditions can be influenced by irrigation in plain areas of Terai. We have not considered irrigation and artificial water storage while setting up the model. In those areas, the supplemental irrigation might have elevated the soil moisture level in irrigated fields. Similarly, the soil moisture derived from the model was not validated independently due to the lack of the observed data and validation was only limited to discharge and evaporation data.

[Comment]
The paper analyzed the spatial drought events. I did not see any spatial distribution of the drought events. The authors should show the spatial drought condition using a map.

[Response]

Thank you for pointing out the important aspects of spatial maps. 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 the spatial maps, 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.

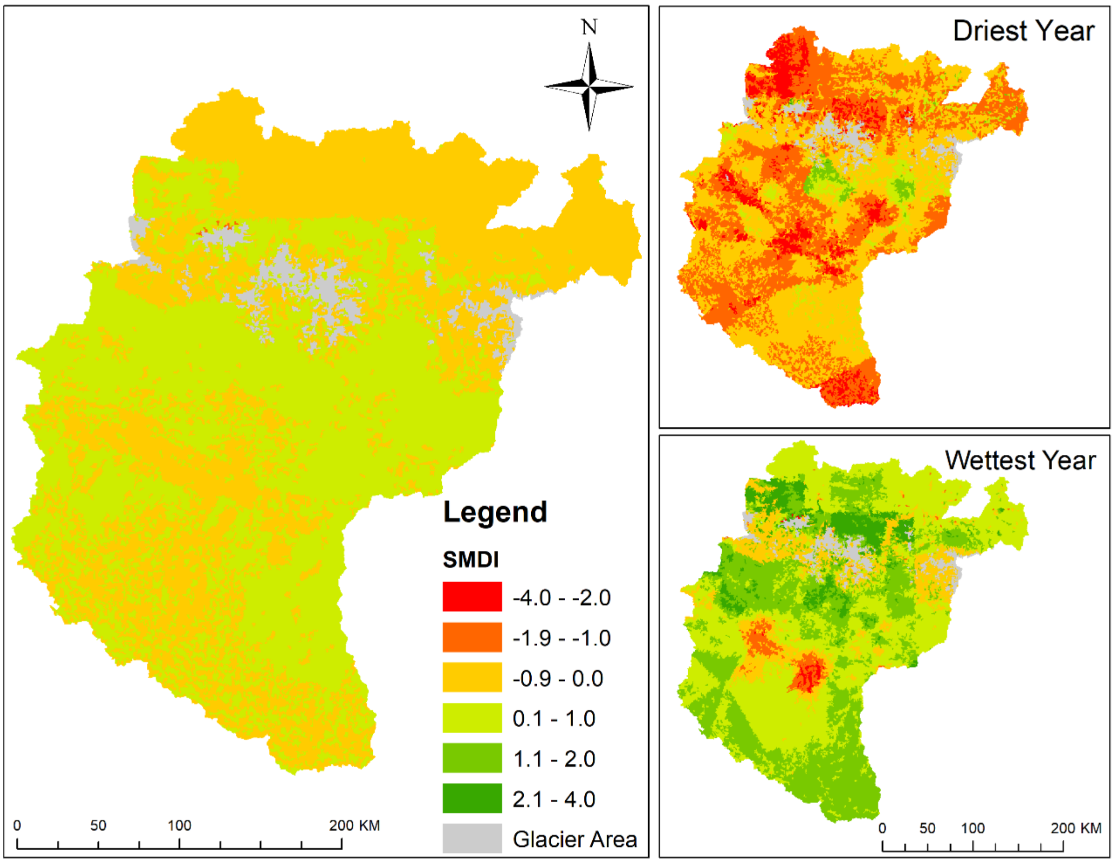

Figure 8: Spatial maps of average annual SMDI (1980-2007), dryest year (1992) and wettest year (1998).

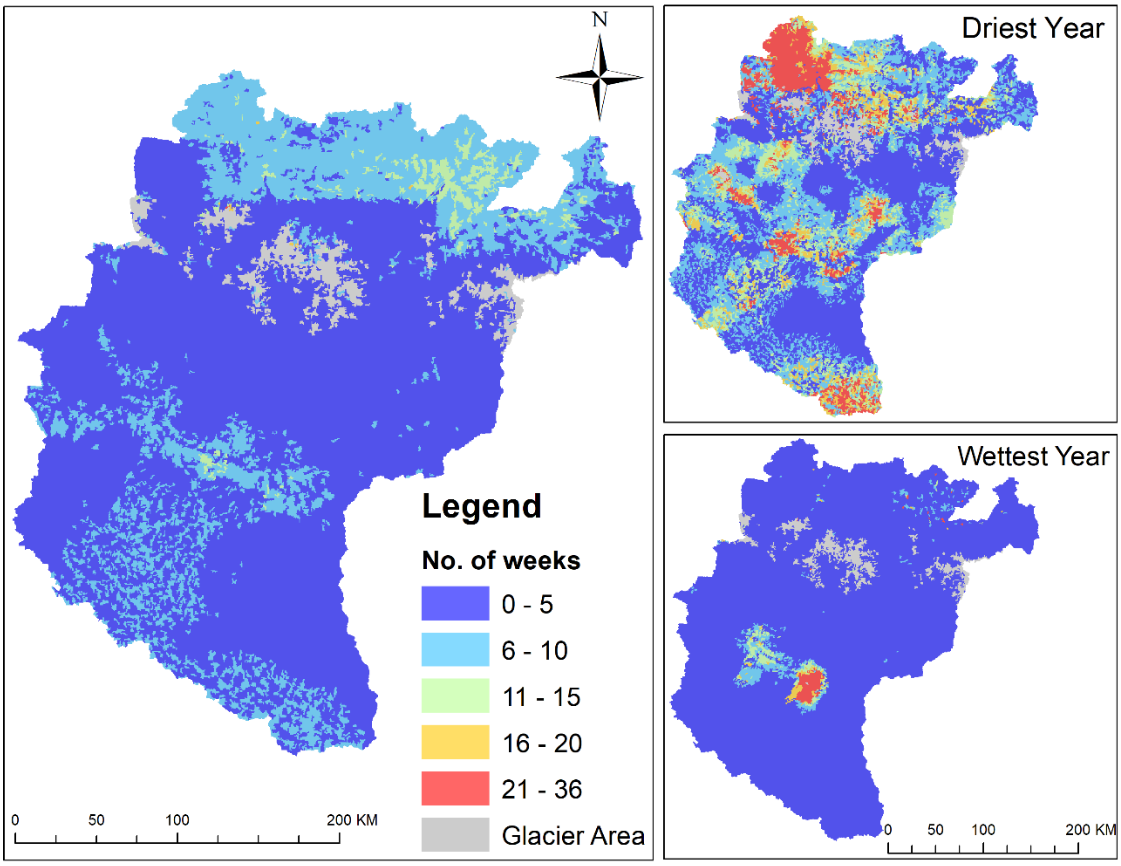

Figure 11: Spatial maps of average duration of drought i.e. SMDI < -3.0, dryest year (1992) and wettest year (1998).

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]
Section 4.2.5, historical incidence of drought. This section should be used to assess the applicability of SMDI. Therefore, it is better set at the beginning of section 4.2.

[Response]
Thanks for pointing out this important aspect. In combination with reviewer #2 (last comment) and #3 comments, we have now developed a new section 'Discussion' after 'Result'. Along with new information on discussion, we also highlighted three aspects in discussion: 1) Discussion related to results 2) uncertainty and limitation and 3) historical incidences of drought

The new discussion section reads as:

5 Discussion

The application of the J2000 model in transboundary Koshi river basin with the three physiographic regions has enabled to understand the spatial and temporal variation of soil moisture conditions and related droughts. The distinct pattern of soil moisture influenced by both temperature and precipitation conditions are reflected in four seasons and distinct physiographic conditions.

In the trans-Himalaya region, the dry conditions in the winter season from 2001–2006 may be attributed to the low winter precipitation (Figure 5). Three of the lowest precipitation years during the study period occurred after 1998 (1998, 2005, and 2007). The average surface temperature has also steadily increased in the winter season during this period. Only positive temperature anomalies are observed after 1998 in the winter season. In the pre-monsoon season, the dry conditions are probably derived from the temperature, which increased after 1998 up to 2004 (Figure 6). The three lowest years of monsoon precipitation occurred during 1982, 1983, and 2006, which coincides with the dry conditions in that period. A positive temperature anomaly is seen during the monsoon after 1987 barring a few years such as 1992, 1996, and 1999, which also translates into dry conditions during those periods. However, the interannual variation in precipitation is low for the monsoon season in the region. The data shows a positive post-monsoon temperature anomaly after 1999, except for 2004, which translates into the dry conditions in that period. Post-monsoon precipitation is highly variable in the region leading to high interannual variability in dryness in the region.

In the mountains, the three years with the lowest precipitation in the winter season were 1998, 2004, and 2007 (Figure 5), which directly translates into dry conditions in the region. The winter temperature also shows positive anomalies after 1997 (Figure 6). The three years with the lowest precipitation in the pre-monsoon season were 1992, 1995, and 1996, whereas positive temperature anomalies can be seen for most years after 1990. This correlates with the dry conditions in those periods in the region. Post-monsoon precipitation is highly variable in this region (Figure 5). The three years with the lowest post-monsoon precipitation are 1981, 1991, and 1994. The temperature anomalies are also positive during 1998–2003, which is one of the reasons for the dry conditions in this period.

In the plains, no precipitation was recorded in winter of 1998, 2005, and 2007 (Figure 2), which directly translates into severe dry conditions during those years in the region. Winter temperatures also show positive anomalies after 1997 (Figure 6), except during 2002. The three years with the lowest precipitation in the pre-monsoon season, and a consequent positive temperature anomaly, were 1994–1996. This correlates with dry conditions in those periods. Only positive temperature anomalies can be seen in the pre-monsoon season after 1998. The dry conditions in the post-monsoon season may be attributed to the highly variable precipitation in this region (Figure 5) with values ranging between 50–300 mm. The three years with the lowest post-monsoon precipitation were 1981, 1984, and 1997. The temperature anomalies are also positive in most years after 1992.

From the period of 1981-2007, the year 1992 is the dryest year over the whole basin and the maximum number of weeks of drought occurrence (i.e 8.5 weeks). On contrary, the year 1998 is the wettest year and lowest number of weeks of drought occurrence (i.e 1.2 weeks (Figure 8 and 11; and Table 3 and 4).

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).

At the basin scale, the higher incidence of soil moisture deficit is in the plains which is mainly due to higher temperatures. In the trans-Himalaya, droughts persist for a higher number of weeks in the seasons mainly due to low precipitation. A higher frequency of drought is observed in the winter and pre-monsoon seasons. The monsoon season is least affected by the drought due to abundant precipitation at this time but even so, about one-quarter of the season is affected (Figure 12). There is an increasing trend in the frequency of drought in recent years during the winter and the pre-monsoon season. Similarly, the extent of maximum area covered under drought is higher during the monsoon season and in some years have covered more than half of the basin area. This indicates that although precipitation brings wetness during the monsoon season, drought could reach more than 25% of the region for at least one week.

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 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. 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).

Historical incidences of drought

We also examined historical drought events and their impacts on agriculture based on the published literature. The soil moisture drought derived by our study also matches the historical drought events in Nepal mainly of 2005-2006 (winter) and 1992 and 2005 (summer).

Dahal et al. (2016) and Shrestha et al. (2017) reported dry spells in central Nepal during the winter of 2005–2006 and their implications for agriculture. Our results for the same year also showed that more than 75% of the area in the mountains had an SMDI below –1. Drought (SMDI < –3) occurred in more than half the Koshi River basin's area for more than 40% of the winter. This winter drought of 2005–2006 had the highest spatial coverage in the mountains region over the 28-year period under study (Figures 8 and 10). Dahal et al. (2016) reported less than 30% winter rainfall in 2005–2006, with some areas receiving no precipitation at all. As a consequence, paddy production decreased by 13% compared to the previous year; in some districts in the eastern and central region of Nepal (where the Koshi River basin is located), the reduction in yields was 20%–50%. About 7% of the land under paddy was also reportedly left fallow. Wheat production was adversely affected as well.

As the winter drought of 2005–2006 affected the whole of Nepal, a decrease in paddy and wheat production was also reported from the western region. Subsistence hill and mountain farmers were affected in particular as they tend to be more dependent on rainfed agriculture than farmers in the plains, where irrigation infrastructure is prevalent. Regmi (2007) reported that agricultural production declined by 27%–39% that year in a few districts in the Eastern Development Region compared to the previous year. On average, yields in the Eastern Development Region were about 10% lower than the previous year and almost 15% of the land under paddy was left fallow.

Dahal et al. (2016) and Shrestha et al. (2017) also discussed the summer drought of 2005 in central Nepal. Our analysis also showed the 2005 monsoon drought as the largest in terms of area; more than 50% of the mountains area experienced drought (SMDI < –3.0) in 25% of the weeks (Figure 10).

Bhandari and Panthi (2014) reported the 1992 drought in the monsoon season in western Nepal. The insufficient and untimely rainfall contributed to reduced soil moisture, resulting in an agricultural drought and consequent crop failures. From our analysis, 1992 is reported to have the highest soil moisture deficit for the pre-monsoon and monsoon seasons, during which nearly 90% of the area in the mountains have SMDI values lesser than –1.0, with a higher degree of dryness in the pre-monsoon season (Figure 8). The drought that year (SMDI < –3.0) was the highest for the pre-monsoon season and second-highest for the monsoon season when about 75% and 45% respectively of the basin's area *in the mountains experienced droughts for more than 25% of the weeks. Even during the winter of 1992, 40% of the basin's area suffered drought for 25% of the weeks (and over half the winter season in 25% of the area) (Figure 10). Shrestha et al. (2017) also reported the severe summer drought of 1992, based on SPI indices using both observed and satellite data. Shrestha et al. (2000) showed a good agreement between the deficit rainfall in 1992 in Nepal and the El Nino of 1992 and 1993.*

Although Bhandari and Panthi (2014)'s analysis was mostly focused on western Nepal, the monsoon's influence extends throughout Nepal, as it passes from eastern through to western Nepal. In the KRB, 1992 was among the three lowest rainfall years in the pre-monsoon and monsoon season. Our assumption is that a similar drought condition have occurred in the eastern mountain districts of the Koshi as well.

Wu et al. (2019) calculated the crop water shortage index (CWSI) based on MODIS-derived evaporation and potential evaporation data for the KRB from 2000 to 2014. The CWSI is found to be consistently increasing from 2000–2006. Our SMDI-based results also indicate a consistent decrease in SMDI since 2001. Although the CSWI and SMDI cannot be directly compared, they both reflect a lack of soil moisture. The year 2006 was found to be one of the severest drought years in both Wu (2019) and our study. Similarly, Hamal et al. 2020 also indicated frequent occurrences of drought in 1992, 1994, 1996, 2001, 2006 which has caused yield loss in whole Nepal.

We did not find information about reported droughts in trans-Himalaya and southern plains for the study period. While the trans-Himalaya part of the KRB has little agriculture land, the presence of irrigation infrastructure in the southern plains makes the context quite different from the mountains, where agriculture is mainly rainfed.

[Comment]

Moreover, when assessing this index, the onset, duration and termination of the drought should be provided by spatial distribution map.

[Response]

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 figures and tables are already provided in connection to the earlier comment).

However, the study of onset and termination of spatial drought will need the development of its own robust methodology. We think this warrants a study of its own and is out of the scope of our study. More specifically, to show the onset and termination of SMDI, we would need to look at the soil moisture values at weekly scale while our aggregation period for this paper is the seasonal scale. Therefore, the onset and termination would be unsuitable to incorporate within the existing methodological approach of this paper, and not included in the revised version.

[Comment

(5) SMDI and SPI were compared and showed some obvious differences. The reasons should be discussed.

[Response]

To address this comment, we have added a paragraph in the discussion section and discussed the differences in SMDI and SPI. The paragraph in the discussion section 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).

[Comment]

(6) Discussion is a very important part for a paper, and should be in a separate section.

[Response]

In relation to an earlier comment, now we have developed a separate section for ‘Discussion’ and highlighted three aspects: 1) Discussion related to results 2) uncertainty and limitation and 3) historical incidences of drought

The new discussion section is already pasted above in relation to the earlier comment:

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

Santosh Nepal et al.

Santosh.Nepal@icimod.org

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:

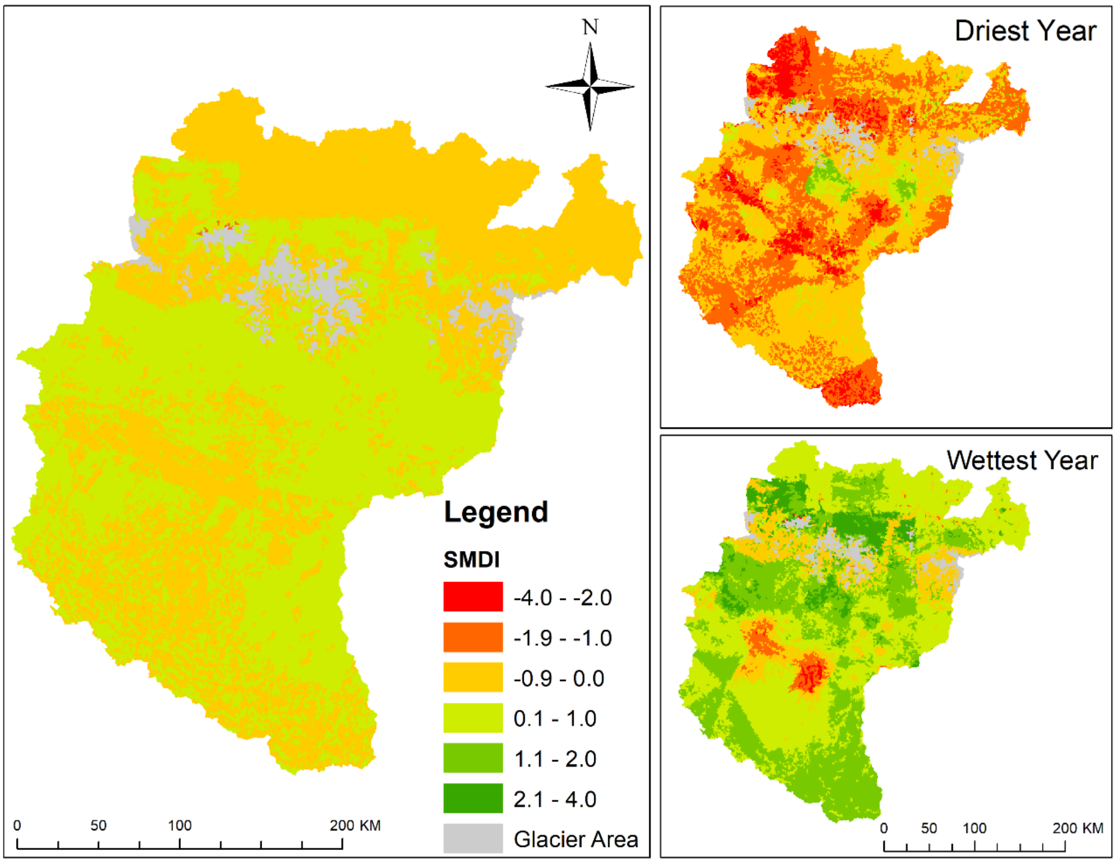

Figure 8: Spatial maps of average annual SMDI (1980-2007), dryest year (1992) and wettest year (1998).

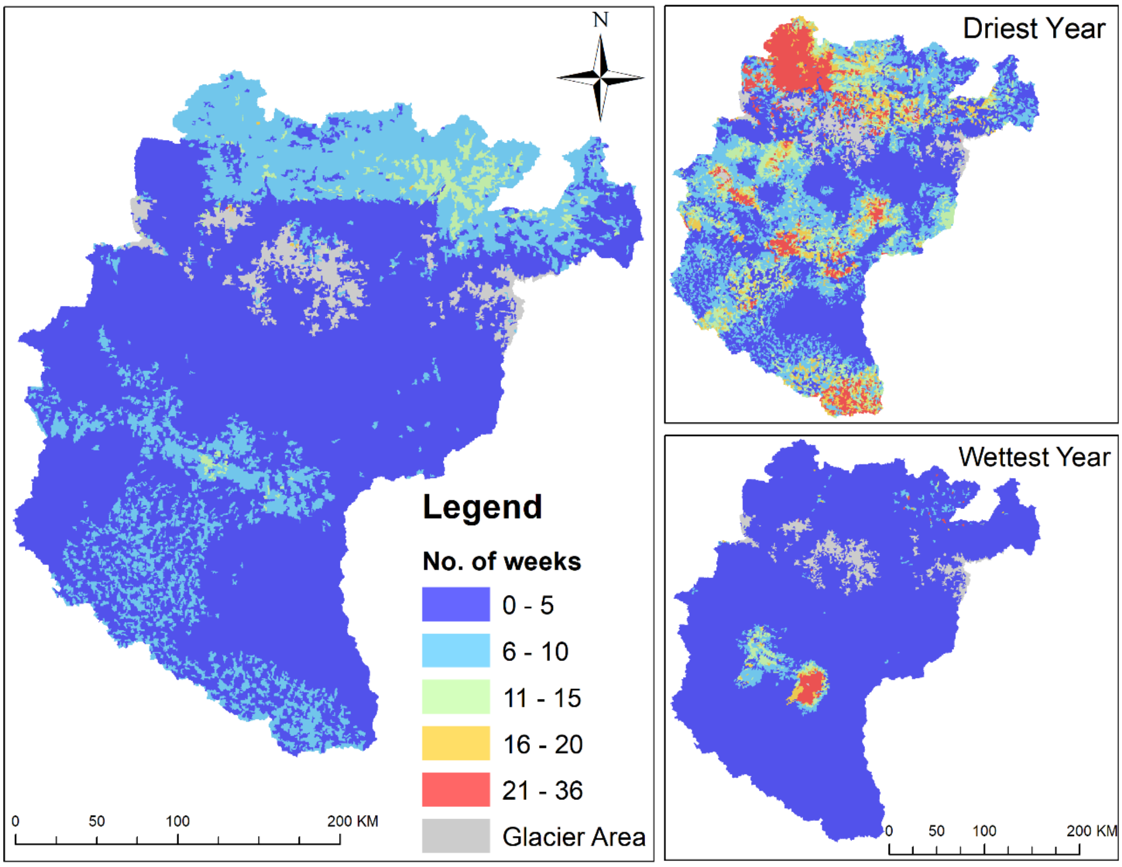

Figure 11: Spatial maps of average duration of drought i.e. SMDI < -3.0, dryest year (1992) and wettest year (1998).

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:

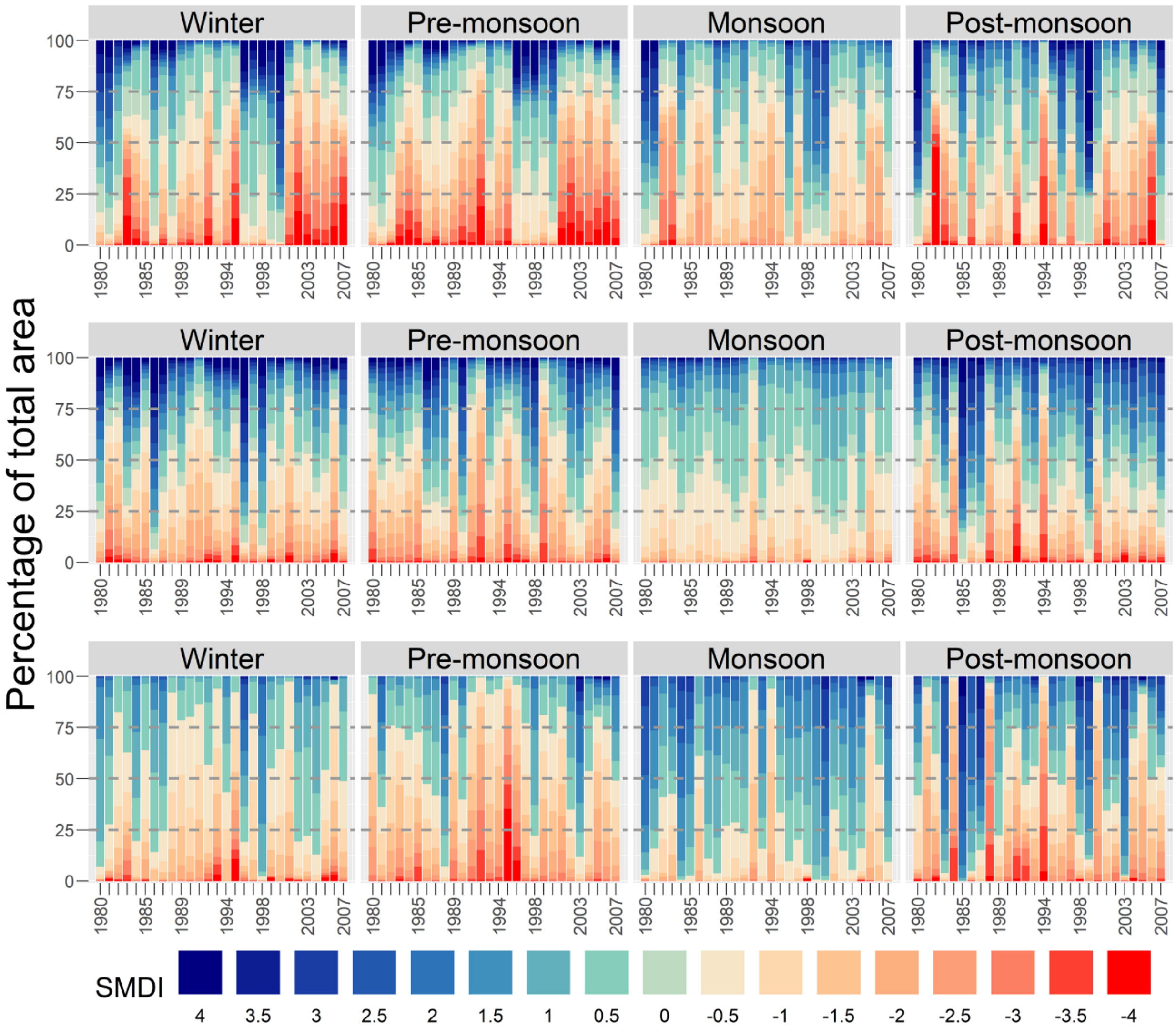

Figure 9 Spatial and seasonal variability of the SMDI in trans-Himalaya (top), the mountains (middle), and the plains (bottom)
Note: Each colour band shows the respective HRU's area combined.

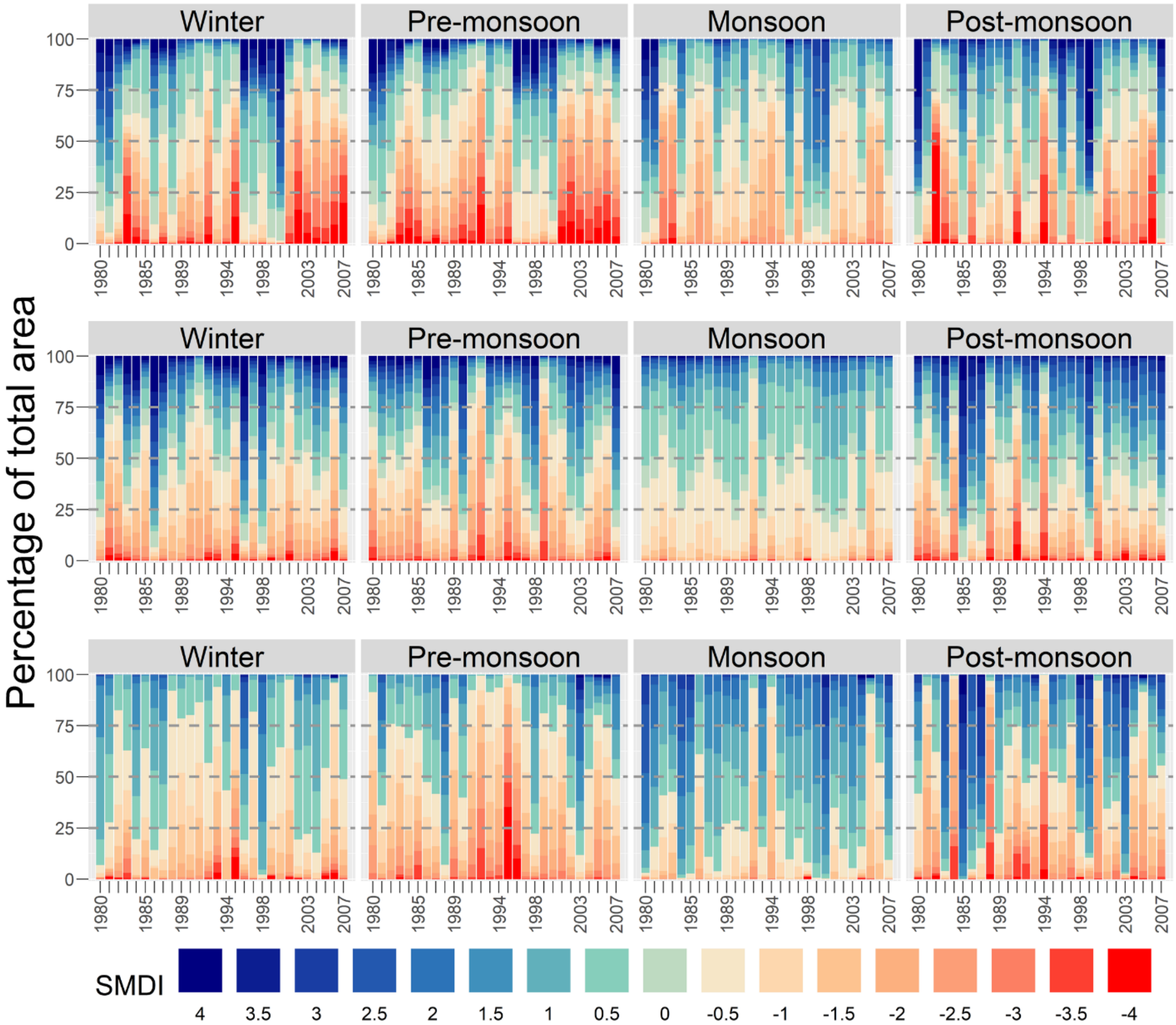

Figure 10 Spatial and seasonal variability of the SPI in the trans-Himalaya (top), the mountains (middle), and the plains (bottom)

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

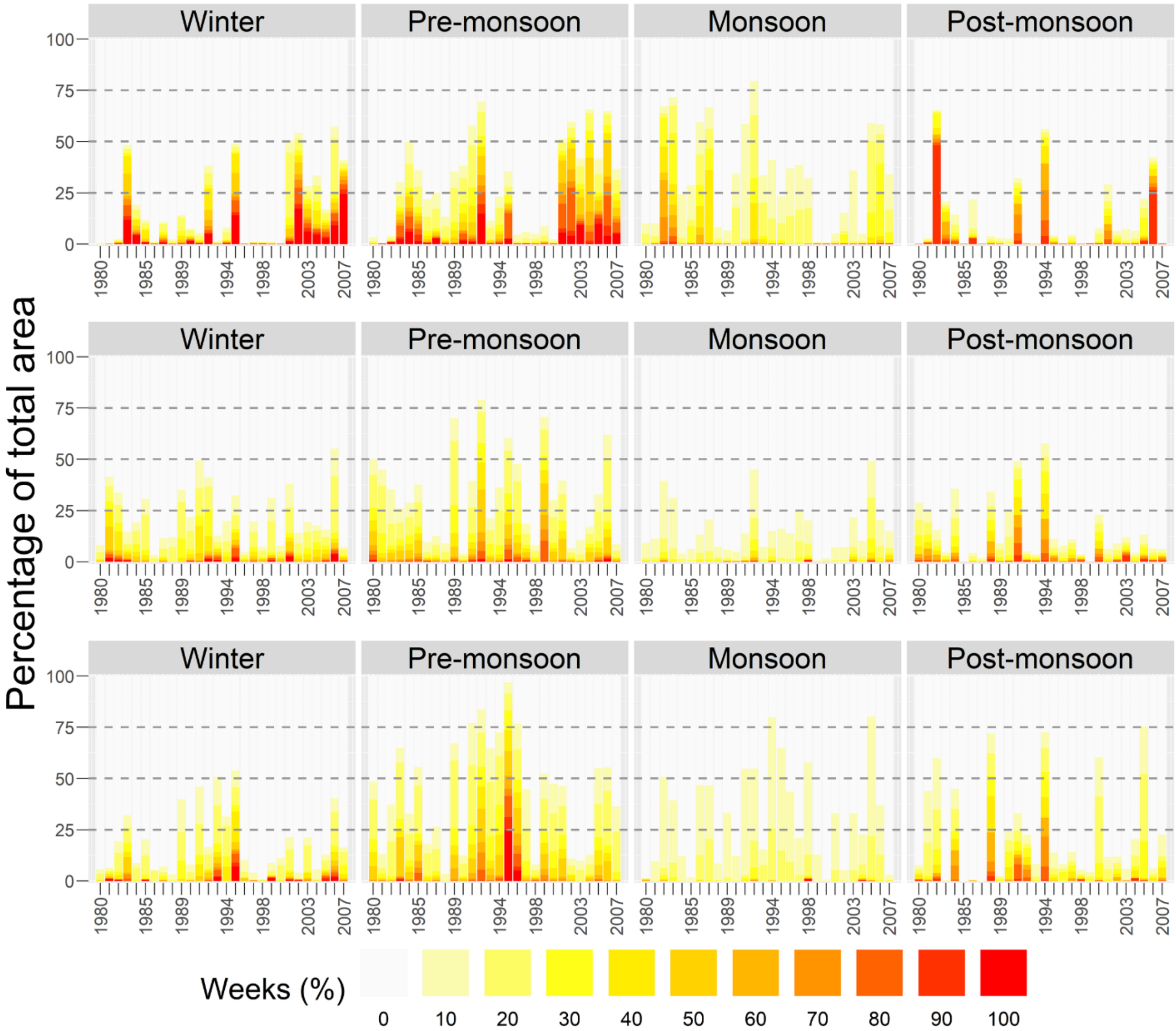

Figure 12: Percentage of weeks with severe drought in the trans-Himalaya (top), the mountains (middle), and the plains (bottom)
Note: Each colour band shows the respective HRU's area combined