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

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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

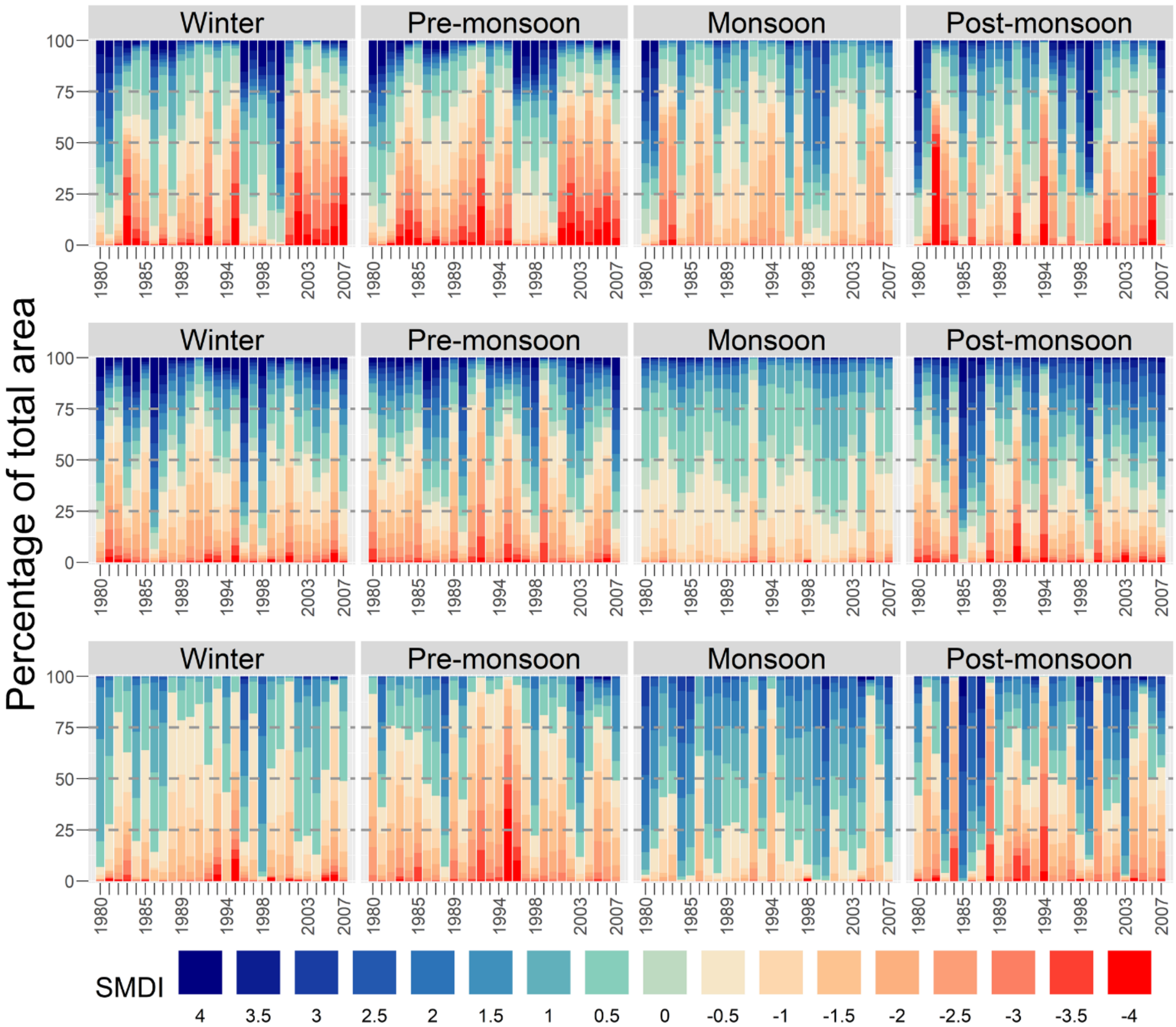

Figure 9 Spatial and seasonal variability of the SMDI in trans-Himalaya (top), the mountains (middle), and the plains (bottom)
Note: Each colour band shows the respective HRU’s area combined.

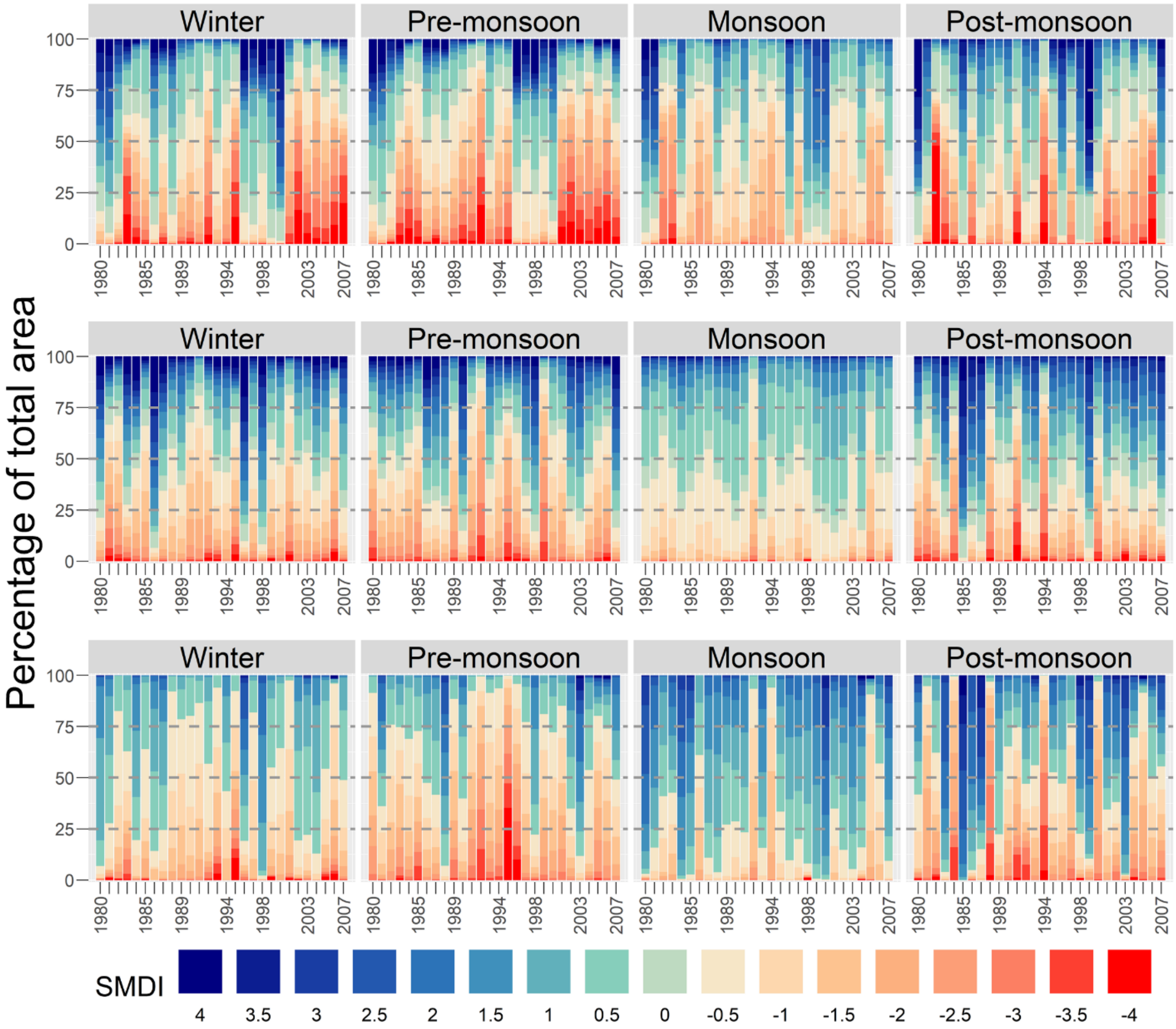

Figure 10 Spatial and seasonal variability of the SPI in the trans-Himalaya (top), the mountains (middle), and the plains (bottom)

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

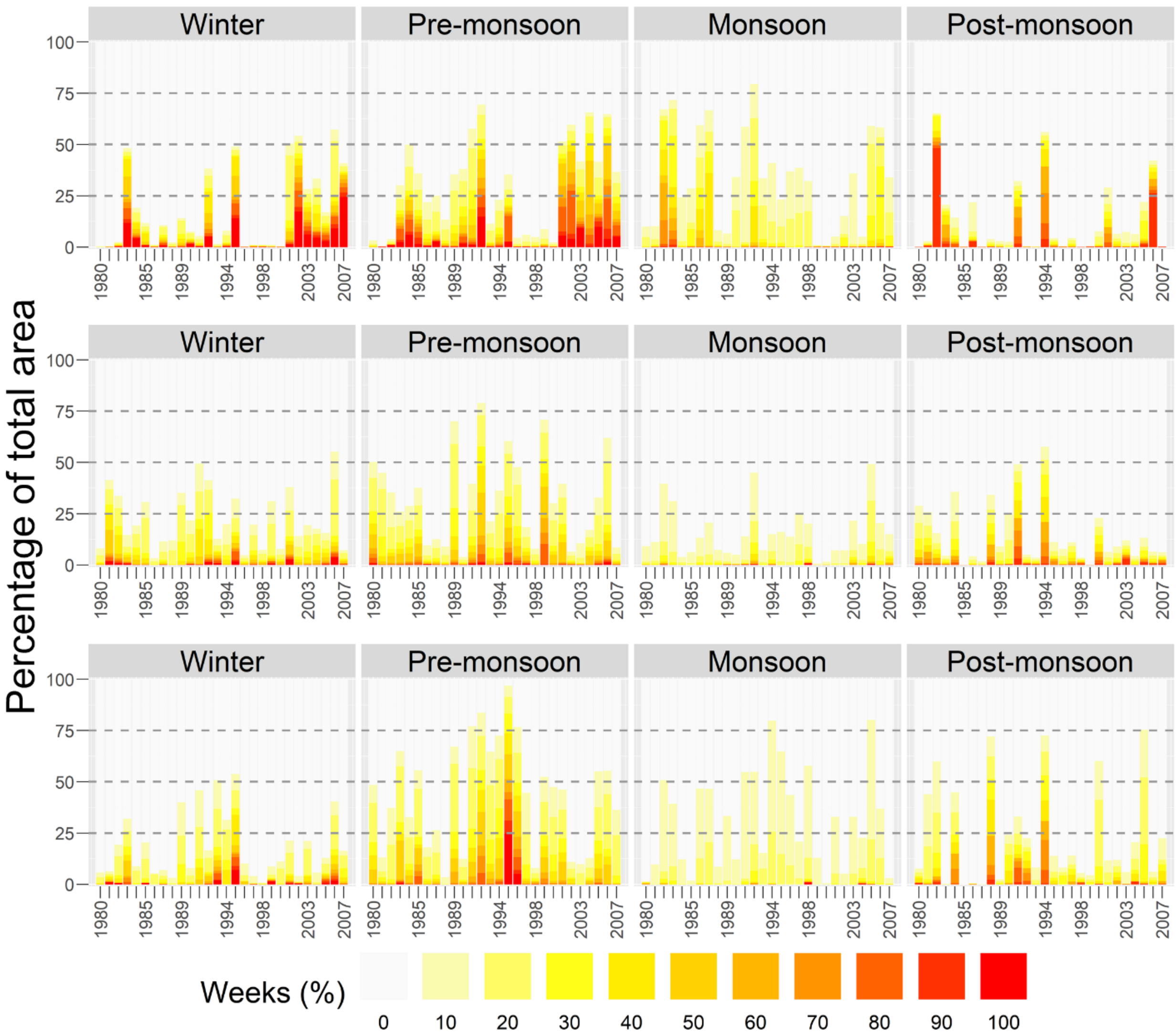

Figure 12: Percentage of weeks with severe drought in the trans-Himalaya (top), mountains (middle), and plains (bottom)
Note: Each colour band shows the respective HRU's area combined