Emergence of significant soil moisture depletion in the near future

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Keywords: soil moisture, emergence, timing of depletion, ISI-MIP, drying, near future prediction

Abstract

Declining soil moisture related to climate change can greatly affect social, economic, environmental, and hydrological processes, as well as extreme weather events. Hence, it is imperative to understand the timing of significant soil moisture drying under future climate change. Compared to spatial variations in soil moisture drying, however, our understanding of temporal variations remain unclear. In the present study, the timing of significant soil moisture depletion (SSD) is predicted using the soil moisture projection (0–50 cm depth) from the 30 Inter-Sectoral Impact Model Intercomparison Project fast-track outputs under the representative concentration pathways (RCPs) 2.6 and 8.5. Under both RCP scenarios, the ensemble medians of the projections show the emergence of the timing of SSD in Western Europe, Eastern United States, South America, Sub-Saharan Africa, Australia, and Southern China over 40 years (<year 2060). In 2020, the Eastern United States, Australia, and Southern China already experienced SSD. These findings concur with those of previous observational studies on rapid droughts in the mid to late 2010s. On average, approximately 15% and 29% of the global land area will experience SSD under RCP 2.6 and RCP 8.5, respectively, by the end of the 21st century. A comparison of the timing of SSD in under RCP 8.5 with the timing of the global warming target (1.5 °C) shows that approximately 10% of the global land area will experience SSD before the 1.5 °C warming target is achieved. However, this will double to approximately 23% if the global warming level reaches 2 °C. The results of this study suggest that near-future predictions of the timing of SSD should be considered to mitigate its negative impacts.

1. Introduction

Soil moisture is generally referred to as the amount of water in the unsaturated zone and is a fundamental variable in atmospheric and hydrological sciences as it significantly influences the energy balance at the land surface (Oki and Kim 2016). It plays an important role in controlling the fluxes of water and energy between land and atmosphere interactions, with consequent impacts on climatic, ecological, and hydrological systems (Shellito et al 2016, Srivastava 2017, Yang et al 2018, Teuling 2018). Changes in soil moisture and the related feedback mechanisms have drawn the attention of climate scientists and hydrologists because soil moisture drying potentially leads to agricultural drought, and can also intensify heatwaves under global warming (Gu et al 2019, Merrifield et al 2019). Soil moisture drying can heat the land surface and near-surface air by increasing the portion of sensible heat in the surface energy budget, which is consistent with the reduction of evapotranspiration and latent heat release (Seneviratne et al 2010). This also amplifies the persistence of extreme weather events such as droughts and heat waves (Hauser et al 2016, Mccoll et al 2017, Orth and Destouni 2018). Therefore, soil moisture drying is highly relevant to
land-climate systems and has further impacts upon extreme weather events.

As human-induced global warming intensifies, terrestrial water availability decreases (Padrón et al 2020); this has a significant impact on land ecosystems as well as human society. As soil moisture is a key water storage component, it is necessary to understand projected soil moisture drying under a future warming climate to plan and implement reliable mitigation and adaptation policies (Seneviratne et al 2010, Berg et al 2017, Vogel et al 2018). Previous studies predicted future soil moisture changes by using regional and global climate models (Quesada et al 2012, Merrifield et al 2019). In future, changes in soil moisture variability under global warming will depend upon the extent of the changes in soil moisture and its consequences (Rind et al 1997). The land-atmosphere projections under various warming scenarios indicate that soil moisture will decrease in many regions, in accordance with the projected near-surface drying, despite the slight increase in precipitation over the land surface (Fu and Feng 2014, Lin et al 2015, Scheff and Frierson 2015, Berg et al 2017).

Future projections in soil moisture changes are determined based on the difference in soil moisture for a particular period of the 21st century relative to the present climate; for example, the average soil content of 2081–2100 minus the average soil content of 1986–2005. This type of projection can capture the spatial variability of soil moisture changes (IPCC 2013, Berg et al 2017, Lu et al 2019). Understanding the temporal aspect of soil moisture drying is necessary to devise mitigation policies to reduce its impacts; however, the temporal aspects are yet to be completely evaluated.

Therefore, the temporal evaluation of soil moisture depletion could have a strong implication in planning disciplines related to surface water availability such as agriculture, food security, and ground water resources. These are all critical components of daily life, as well as significantly impact climate. This study aims to predict the timing of significant soil moisture depletion (SSD) relative to the present conditions using a widely used metric. This metric is the time of emergence approach and is used to capture the timing of anthropogenic climate change beyond natural variability (Hawkins and Sutton 2012, Lehner et al 2017, Park et al 2018). We compared the timing of soil moisture drying with the timing of the global warming target temperatures at 1.5 °C and 2.0 °C, and defined the regions with significant soil moisture changes, based on the target warming.

2. Data and methods

2.1. Projections of soil moisture and surface air temperatures

We used monthly soil moisture outputs (0–50 cm-depth) obtained from the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP) fast track ensemble experiments for the historical period of 1971–2005, and for two future climate scenarios of 2006–2009 under the lowest and highest radiative forcing. The two future scenarios are employed from representative concentration pathways (RCPs) 2.6 and 8.5, which are termed according to radiative forcing target levels of 2.6 and 8.5 W m−2 by 2100, respectively (Warszawski et al 2014). For the historical period, RCP 2.6 and RCP 8.5, the soil moisture dataset has 30 ensemble members as a result of the combination of six global impact models (GIMs), with five general circulation models (GCMs) (tables S1 and S2, which are available online at stacks.iop.org/ERL/15/124048/mmedia).

The six GIMs in the ISI-MIP were forced with climate data from the six GCMs of the historical period and two RCP scenarios in the Coupled Model Intercomparison Project 5 (CMIP 5). The climate dataset of five GCMs in table S1 (Spatial ranges from 1.25° to 2.8125°) were spatially interpolated to 0.5° × 0.5° in latitude and longitude and were bias corrected to provide the input data for the GIMs. The bias corrected dataset included statistical distribution matched to the observation-based Water and Global Change forcing data (Weedon et al 2011, Hempel et al 2013). These climate datasets were individually employed as a boundary for the six GIMs. The soil moisture dataset and monthly surface air temperatures of the five GCMs for the same period were obtained to project the time when the global mean temperature reached 1.5 °C and 2 °C above the pre-industrial level (t1.5 and t2) under both the RCP 2.6 and RCP 8.5 scenarios (table S3). An equally weighted 20 year moving average was applied to both soil moisture and surface air temperature data from 1986–2005 to 2080–2099 for eliminating interannual fluctuations (Park et al 2018). Individual 20 year periods were indexed as the last year. The t1.5 was determined by the year that the increment of the 20 year running average of the global mean temperature first exceeded 0.9 °C, relative to 1986–2005, because the period 1986–2005 was warmer than the pre-industrial level by 0.6 °C (Hawkins et al 2017).

2.2. Timing of significant soil moisture depletion

The timing of SSD under the RCP 2.6 and RCP 8.5 scenarios was calculated from the first time when a decrease in soil moisture exceeded the natural variability derived from the reference period, which ranged from 1971 to 2005. It can be described as a signal-to-noise ratio (S/N) (Hawkins and Sutton 2012, Lehner et al 2017, Park et al 2018).

\[
\text{Signal to noise ratio} = \frac{\Delta_{SM}}{\sigma_{SM}} \quad (1)
\]

where \(\Delta_{SM}\) is the soil moisture changes in 20 year mean of soil moisture relative to the reference period,
and $\sigma_{SM}$ is the standard deviation of the reference period of the projections.

$\Delta_{SM}$ could be computed by the differences between each 20 year running average of annual mean soil moisture starting from 2006 (1987–2006) to 2099 (2080–2099), and the present condition of annual mean soil moisture (1986–2005). $\sigma_{SM}$ was calculated by the standard deviation of the annual mean soil moisture for the 35 year period from each soil moisture output of the 30 individual ISI-MIP projections (1971–2005) (Hawkins and Sutton 2011, 2012, Park et al 2018). To estimate the timing of SSD from multi-model outputs, we defined the S/N threshold as below $-0.5$. We first categorized the thirty individual ISI-MIP projections into the following three subsets before calculating the timing of SSD: (a) significant soil moisture decrease ($S/N < -0.5$), (b) significant soil moisture increase ($S/N > 0.5$), and (c) no significant soil moisture changes. To calculate the timing of SSD, each grid cell should satisfy that at least 50% of the 30 ISI-MIP models were subset 1 and less than 33% of the 30 ISI-MIP models were subset 2. The first and second subsets of likelihood terms were derived from the outcomes of the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (Cubasch et al 2013). The probabilities of the statement in subset 1 and subset 2 were referred to as likely and unlikely. When each grid cell satisfied the above two conditions, the median, 16th, and 84th percentile years of SSD were computed from the 30 ISI-MIP model outputs. The calculation of the median years, 16th, and 84th percentile of SSD assumed that SSD in any model, including subset 2 and subset 3, occurred later than 2100. For example, if a grid cell had the timing of SSD occurrence in twenty-five models, and no emergence in five models (subsets 2 and 3), we calculated the median, 16th, and 84th percentile year of SSD from the thirty ISI-MIP models with the year of five models set to later than 2100. The 16%–84% range year of SSD was calculated as the differences between the 16th and 84th percentile year of SSD. However, when the 84th percentile year of SSD was later than 2100, the 16%–84% range year of SSD was not computed.

### 3. Results

The multi-model median projections of soil moisture change (0–50 cm-depth) under the RCP 2.6 and RCP 8.5 scenarios were estimated between the present (1986–2005) and the end of the 21st century (2080–2099) (figures 1 (a) and (b)). Approximately 47% and 52% of the global land area is expected to experience soil moisture deficits at the end of the 21st century in both the RCP 2.6 and RCP 8.5 scenarios, respectively. Spatial patterns of soil moisture changes indicate large-scale soil moisture drying, especially in South America (SAM), North America, Europe, East Asia, South Africa, and Australia (AUS), with soil moisture wetting in a limited portion of Russia, Central Asia, and East Africa. The drying and wetting of soil moisture are similarly distributed between the two RCP scenarios, but the magnitude of soil moisture change is proportional to the increase in radiative forcing. For example, the area of soil moisture drying in Western Europe (WEU) under RCP 8.5 (approximately $-30\%$) is approximately 20% drier than under RCP 2.6 (approximately $-6\%$) at the end of the 21st century. These results are consistent with those of previous studies (IPCC 2013, Berg et al 2017, Lu et al 2019).

Figures 1(c) and (d) show the multi-model median timing of SSD under RCP 2.6 and RCP 8.5. The spatial distributions of 16%–84% range year of SSD for RCP 2.6 and RCP 8.5 are illustrated in figure S1. The 16%–84% range years of SSD in figure S1 are shown for the regions where the 84th percentile year of SSD is earlier than 2100. The results for the timing of SSD range from 2022 to 2099 in RCP 2.6, and from 2016 to 2079 in RCP 8.5. The spatial patterns of SSD are distributed in the Eastern United States (EUS), SAM, WEU, Sub-Saharan Africa (SSA), Southern China (SCH), and AUS under both RCP scenarios. The regional mean for the multi-model median year of SSD shows EUS for 2061 and 2061, SAM for 2059 and 2056, WEU for 2048 and 2057, SSA for 2065 and 2067, SCH for 2066 and 2054, and AUS for 2059 and 2062 by RCP 2.6 and RCP 8.5, respectively. The 16%–84% range years of SSD in figure S1(b) indicate that the earlier year of SSD regions in figure 1(d) are related to a smaller uncertainty, and those regions are likely to experience significant soil moisture drying during the 21st century. The 16%–84% range years are not shown in figure 1(a) because the 84th percentile year in most regions is after 2100. These results show that the timing of SSD projection in RCP 2.6 has a larger uncertainty, and this larger uncertainty is likely to lead to the late median timing of SSD. Figures 1(c) and (d) indicate that the regional mean years of SSD in WEU, SSA, and AUS under RCP 2.6 are three to nine years prior than under RCP 8.5, while the SAM and SCH regions in RCP 2.6 are 3–12 years later than in RCP 8.5. These five regions are different based on the timing of SSD from the perspective of both the regions as well as the RCP scenarios. However, the spatial distribution of the SSD area is more widespread in RCP 8.5 than in RCP 2.6. Figures 1(e) and (f) illustrate the remaining years of SSD, which are the differences between the median year of SSD and the present year (2020). The remaining periods for the six regions range from 28 years to 47 years in the regional average through RCP 2.6 and RCP 8.5. Some grids, especially in RCP 8.5, had already experienced or had not yet experienced significant soil moisture drying, ranging from $-4$ to 59 years, compared to the present (2020). Figure 2 illustrates the proportions of the regional mean year of SSD for the thirty ISI-MIP projections.
Figure 1. Spatial distribution of multi-model ensemble median percentage changes in soil moisture (depth = 50 cm) and median SSD years. Global multi-model median percentage changes in soil moisture for the period 2080–2099 (RCP forcing) relative to 1986–2005 (historical forcing) under RCP 2.6 and RCP 8.5 (a) and (b). The median year of soil moisture depletion estimated by 30 ISI-MIP projections under RCP 2.6 and RCP 8.5 (c) and (d). The remaining time for the significant soil moisture drying compared to the present (2020) by RCP 2.6 and RCP 8.5 (e) and (f).

in the six regions selected. These are calculated to identify the regional characteristics with the spread of 30 ISI-MIP projections for the timing of SSD in both the RCP 2.6 and RCP 8.5 scenarios. The proportions of bar charts in the RCP 2.6 and RCP 8.5 indicate regional differences in the timing of SSD. In RCP 2.6, the WEU region has a high proportion of SSD, approximately 60% of the 30 model projections in 2050. The remaining four regions, excluding the SCH region, indicate a high proportion of SSD at 60% to 70% of the 30 model projections in 2060. The median years of the 30 model projections in the regions are approximately 2060, and the SSD in the WEU region is approximately 10 years prior (2048) than the other five regions under RCP 2.6. For the RCP 8.5 scenario, the median timing of the 30 model projections shows regional differences. For example, the WEU, AUS, and SSA regions in RCP 8.5 have a slower SSD time (2–9 years) than RCP 2.6, while the SSD time in the SCH and SAM regions is more rapid for RCP 8.5 (3–12 years) than for RCP 2.6. The gray color bars shown in all regions in figure 2 represent approximately 16.7% of the 30 ISI-MIP model outputs, indicating that soil moisture drying will be insignificant before the end of the 21st century. This constant proportion is caused by all projections using one of the GIMs, MATSIRO, which simulates a small change in soil moisture for all GCM boundary conditions. The GIM projection is likely to have SSD effects on the late median year in both RCP 2.6 and RCP 8.5 scenarios.

The timing of SSD is compared with the timing of the global warming level reaching 1.5 °C. The specific year of the 1.5 °C warming level of the five GCMs is shown in table S3. To compare with the median year of SSD, the median year of the 1.5 °C warming level (t_{1.5}) in the five GCMs was employed. Figures 3(a) and (b) illustrate the comparisons between the timing of SSD and t_{1.5}, where SSD, before reaching t_{1.5}, is distributed over a wider area under RCP 8.5 than under RCP 2.6. The spatial distribution of SSD shows that 36% of the SSD regions developed before the global warming level reached 1.5 °C in RCP 8.5 (figure 3(b)). The timing of SSD is earlier than t_{1.5} in over 14% of the SSD regions in RCP 2.6 (figure 3(a)). Therefore, the spatial patterns of SSD, before reaching t_{1.5}, are significantly different between RCP 2.6 and RCP 8.5. The figure 3 also indicates that under both RCP 2.6 and RCP 8.5, the area of SSD will be markedly reduced if the global warming level is limited to 1.5 °C above the pre-industrial level. The regional spatial patterns for the timing of SSD can be combined into the global land area (figure 4).

The global land area changes in the multi-model projections for the median and 16%–84% range years of SSD under the RCP 2.6 and RCP 8.5 scenarios are shown in figure 4. The median year reaches 1.5 °C and the 2 °C global warming level was calculated using
Figure 2. Proportion of SSD years in ISIMIP simulation ensemble over six regions under the RCP2.6 (left) and RCP 8.5 (right) scenarios. Black dot represents the SSD median timing of the entire ensemble.

Figure 3. Comparison of spatial patterns with the timing of SSD and global warming level reaching 1.5 °C. Red indicates the timing of SSD < $t_{1.5}$, and blue indicates the timing of SSD > $t_{1.5}$.

table S2. The vertical line of 2 °C global warming level in RCP 2.6 is not shown in figure 4 because the median year of 2 °C global warming level is later than 2100. The annual SSD area changes at the end of the 21st century indicate that approximately 15% of the global land area can expect SSD under RCP 2.6, and under RCP 8.5, the land area will nearly double (approximately 28% of land area). The SSD
area in RCP 2.6 continues to increase slightly until the end of the 21st century. The SSD area in RCP 8.5 will dramatically increase by 2060 by approximately 27% of the land area, and then level to 28%. The 16%–84% range of the SSD area change in RCP 2.6 and RCP 8.5 shows clear differences after 2040. The median changes of SSD land area in both RCP 2.6 and RCP 8.5 are slightly skewed to the left in the 16%–84% range of the SSD area change. These are likely to be underestimated by some model projections of SSD that are later than 2100. The open and closed circles in figure 4 indicate the spreads of the 1.5 °C and 2 °C warming level in both the RCP scenarios. The global warming level in RCP 8.5 shows clear differences between the 1.5 °C and 2 °C warming level. The 1.5 °C warming level in RCP 2.6 shows a large uncertainty due to the two GCMs (in table S3); however, the median year of 1.5 °C warming level in the five GCMs has more than 60 year difference to the maximum year of the SSD. In RCP 2.6, less than 3% of the global land area will experience SSD before the global warming level reaches 1.5 °C, and more than 17% of the global land area can expect SSD when the global warming level rises to 2 °C. The global SSD area in RCP 8.5 is projected to be approximately 10% of the global land area before the 1.5 °C warming level. However, it will double (to approximately 23%) if the global warming level reaches 2 °C.

4. Discussion and conclusion

This study investigated future predictions for the timing of SSD by employing soil moisture projections (0–50 cm-depth) of the ISI-MIP fast track framework under the RCP 2.6 and RCP 8.5 scenarios. The median year of SSD shows that most of the soil moisture drying is widespread among different regions (figure 1). These regions are generally equivalent to surface drying regions (e.g. IPCC 2013, Berg et al 2017, Lu et al 2019); the timing of soil moisture drying in most regions is comparatively faster, and occurs before the first half of the 21st century. Takeshima et al (2020) showed that the SSD regions in figures 1(c) and (d) will be drier under 1.5 °C and 2 °C global warming levels because of hydroclimate factors. The net radiation is a key drying driver in the EUS and SCH, while the drying conditions in SAM, WEU, and SSA are exacerbated by precipitation decrease. The timing of SSD for the 30-model ensemble indicates the spatial heterogeneity between regions (figures 1 and 2). These regional differences in the timing of SSD could have potential implications for developing mitigation and adaptation strategies.
under climate change. The future soil moisture drying will result in not only agricultural and ecological loss but also water resource deficit. Because the soil moisture drying leads to agricultural water demands for healthy plant growth, resulting depletion of water resources may put pressure on irrigation demand. Thus, understanding SSD timing is imperative for mitigating its effects on natural resources and implementing water resource policies in an adequate manner. In addition, the regional timing of SSD will provide valuable information for decision makers to understand the effective water resource scope and direction (Brocca et al 2018, Lu et al 2019). Significant spatiotemporal differences were observed in SSD in the six regions (figures 2 and S2). The regionally averaged timing of SSD in the six regions range from 2048 to 2067 for RCP 2.6 and RCP 8.5, respectively (figure 2). Moreover, the predictions for the timing of SSD indicate that SSD has already begun in EUS, SCH, and AUS. To prevent the damage from SSD for the near-term climate, and to offer relevant information for adaptation and planning strategies, it would be better to employ decadal predictions in future research (Meehl et al 2009, 2014, Kirtman et al 2013).

The results demonstrated in figures 3 and 4 suggest that the SSD regions in both RCP 2.6 and RCP 8.5 are significantly reduced when the global warming level is limited to 1.5 °C. The range of the SSD projections in figure 4 demonstrate the difference of the global land area after 2040 between the RCP 2.6 and RCP 8.5 scenarios. The SSD land area changes also indicate the regional differences in the six regions (figure S2). The WEU, SCH, SSA, and SAM regions have the largest increases in the SSD area in both RCP 2.6 and RCP 8.5. The WEU region in RCP 2.6 demonstrates more rapid SSD. The SCH and SAM regions in RCP 8.5 demonstrate more rapid and larger increases in the SSD area when the global warming level reaches 1.5 °C.

This study reveals the time remaining before SSD from the present (2020) onward to provide the information on those regions that require urgent attention. The remaining years until SSD (figure 2(f)) indicate that in some regions in the EUS, SCH, and AUS, with negative or zero years, SSD has already commenced or been experienced. There is evidence of SSD in these regions in recent years. The EUS region experienced flash extreme drought over three months in 2016 (Otkin et al 2018), the SCH region experienced increased drought frequency in the growing seasons during 2000–2016 (Liu et al 2020), and the AUS region, particularly in eastern AUS in early 2018, experienced a rapid drought, which altered wet conditions to dry conditions within a span of two months. These records suggest that our results for the negative remaining years in figure 1(f) have been accurately predicted. They also support our future SSD timing predictions as relatively reliable. Further, although it is generally difficult to validate future predictions, the negative years in figure 2(f) indicate some measure of confirmation for our future predictions.

The SSD regions (figure 2) are present in countries with a major portion of the world’s total populations of approximately 3.8 billion, or equivalent to 49% (World Population Prospects, 2019). The projections for these regions indicate that most regions, excluding SSA, will experience an increase in the percentage of the population aged 65 years or above, with the population of the SSA region doubling by 2050 (Desa 2019). Therefore, these populous and ageing regions are relatively more vulnerable to extreme weather events. Our results highlight that SSD is accelerating under global warming, with increased potential risks of extreme natural hazards. This could cause significant economic and societal damage. The significant and widespread soil moisture deficits in the late 21st century are already well documented in several previous studies (IPCC 2013, Berg et al 2017, Lu et al 2019); however, these are expected to occur far into the future. The results of this study indicate that many regions are likely to experience SSD by 2060 in the RCP 2.6 and RCP 8.5 scenarios. Approximately 10% of the global land area remains with the risk of SSD by 1.5 °C global warming in RCP 8.5; it also shows considerable regional differences with respect to the timing of SSD. These findings could provide information on significant spatiotemporal soil moisture depletion. This information will be useful for planning mitigation policies related to water resources, agriculture, and ecology.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors. The ISIMIP Fast Track data is available upon request to isimip-data@pik-potsdam.de.

Acknowledgments

This work was supported by the Korea Research Fellowship program funded by the Ministry of Science and ICT through the National Research Foundation of Korea (Grant No. 2019H1D3A1A010191988) and the Creative-Pioneering Researchers Program through Seoul National University (SNU). Additional support was provided by Shenzhen Science and Technology Program (Grant No. KQTD201602261958402). H. Kim acknowledges the Grant-in-Aid for Specially promoted Research (Grant No. 16H06291) (JSPS, Japan) and TOUGOU (Grant No. JPMXD0717935457) (MEXT, Japan). We acknowledge the World Climate Research Programme’s Working Group on Coupled Modelling, which is responsible for CMIP. We thank the ISIMIP coordination team for their efforts in producing,
coordinating, and making the model outputs publicly available (listed in tables S1 and S2).

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