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Assessing the soil moisture-precipitation feedback in Australia: CYGNSS observations

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Abstract

Previous modelling and case studies highlight the impacts of antecedent soil moisture on precipitation, showing the connection between the anomalous land surface and atmospheric conditions. However, observational evidence is lacking, especially on daily timescales, primarily due to the difficulty in assessing the interaction between soil moisture and atmospheric variability and dataset quality. Using satellite retrievals, this study investigates the relationship between soil moisture and next-day precipitation in Australia. Analysing the 5 year soil moisture data from the Cyclone Global Navigation Satellite System, we find that soil moisture anomalies influence next-day precipitation probability where higher soil moisture is associated with a higher probability of precipitation, even allowing for precipitation persistence. We also find that this feedback is generally positive in northern Australia but slightly negative in the southern regions, suggesting regional dependence. Linkages between the persistence of dry/wet soil moisture days and the possibility of wildfires and floods are also discussed. These findings have direct implications for the management and predictions of extreme conditions.

1. Introduction

Soil moisture is the water content in surface soils and plays an important role in atmospheric and hydrological processes (Shao *et al* 1997). Previous studies have shown that dry soils could intensify upper-level anticyclonic anomalies due to higher sensible heat flux, which leads to higher temperatures at the surface (Fischer *et al* 2007) and, therefore, is critical to consider for heatwave studies (e.g. Hirschi *et al* 2011, Mueller and Seneviratne 2012, Perkins *et al* 2015). The persistence of dry soil can increase the likelihood of droughts (e.g. Koster *et al* 2004), extreme temperatures (Nicholls and Larsen 2011, Whan *et al* 2015, Berg *et al* 2016, Ganeshi *et al* 2023), and wildfires (O *et al* 2020). On the other hand, higher soil moisture can modulate changes in flood timing (Sharma *et al* 2018, Wasko *et al* 2020) and magnitude (Wasko and Nathan 2019). In addition, soil moisture has been shown to influence groundwater resources (e.g. Erler *et al* 2019) and a post-landfall storm (Zhang *et al* 2019), so examining soil moisture and its interaction/relationship with other climate variables is relevant to regional and large-scale climate variability.

Precipitation has undoubtedly made significant impacts on soil moisture, while the impact of soil moisture on precipitation is more complex (Seneviratne *et al* 2010, Wei and Dirmeyer 2012). For example, positive feedback between soil moisture and precipitation could increase the duration of severe dry and wet periods (i.e. droughts and floods), as drier soils would lead to a lower precipitation likelihood (Tuttle and Salvucci 2016), while negative feedback exhibits the opposite. Major research focus in this area has shown that soil moisture can modify atmospheric processes, including precipitation, on various spatial scales and ranging from hourly to seasonal timescales (e.g. Tuttle and Salvucci 2016, 2017, Williams 2019; see also Liu *et al* 2022). Understanding the feedback between soil moisture and precipitation thus has direct implications for drought and flood emergency management and for developing tools for predicting extreme weather.

Despite its importance, feedback between soil moisture and precipitation is a less well-understood aspect of the land-atmosphere interaction in Australia, a water-limited ecosystem region where agricultural activity depends on water resource management (Kala *et al* 2015). The current understanding of soil moisture in Australia broadly extends from the interpretation of ground-based observation, which is sparsely distributed (Cai *et al* 2022). Numerical models show inconsistency in their simulation response to perturbed soil moisture (Kala *et al* 2015). Previous studies show the large-scale variations of soil moisture associated with precipitation changes due to El Niño–Southern Oscillation (ENSO) (Jones and Trewin 2000). And it still needs to be determined how the soil moisture impacts precipitation on a daily basis. In particular, whether and how the soil moisture impacts the next-day precipitation. This motivates our current study.

Here, we investigate the impacts of soil moisture on next-day precipitation using the Cyclone Global Navigation Satellite System (CYGNSS; Ruf *et al* 2016) dataset. CYGNSS is a relatively new tool (i.e. launched in December 2016) that can address outstanding questions related to land and atmosphere feedback, as it can provide better spatial and temporal resolutions. We begin this paper with a basic assessment of the spatiotemporal distribution of soil moisture from CYGNSS using the current 5 year data record (2018–2022), focusing on the lowest and highest values. We then examine the feedback between soil moisture and next-day precipitation at each location and compare the results between monsoon and break periods. Finally, we elaborate on the linkage between the persistence of dry/wet soil moisture days and the fire danger index (FDI) and the river discharge to investigate the role of soil moisture in potentially influencing flood, drought, and wildfire probability over the Australian continent. Conclusions and discussions follow.

2. Data and methods

2.1. Data

We used the following data spanning January 2018 to December 2022. All the daily data were re-gridded to a 0.5 × 0.5 latitude-longitude grid to be consistent between datasets and to avoid impacts from small-scale processes before subsequent processing.

2.1.1. Soil moisture

We use the University Corporation for Atmospheric Research (UCAR) and the University of Colorado at Boulder soil moisture version 1.0 from the recently launched National Aeronautics and Space Administration (NASA) CYGNSS (Chew and Small 2020, CYGNSS 2020). The CYGNSS soil moisture is derived from the volumetric water content estimate for soils between 0–5 cm depth and covers most of the tropics (38° S–38° N) at daily time steps. CYGNSS provides unprecedented spatial and temporal resolution [i.e. approximate 3 hour revisit time and 25 km effective resolution; see also Ruf *et al* (2019) and Stephens *et al* (2020)]. Compared to previous satellites, CYGNSS products are not significantly affected by precipitation (Ruf and Balasubramaniam 2018), which is a distinct advantage over traditional spaceborne scatterometer-based retrievals (e.g. Weissman *et al* 2012). In addition, the CYGNSS product also incorporates real-time monitoring of direct global positioning system (GPS) signal strength and GPS satellite power fluctuations, although the current version of the soil moisture product does not incorporate the temporal variation of GPS effective isotropic radiated power parameter into its calibrations. It thus produces more accurate data retrievals than previous satellite products (Ruf *et al* 2016). Given these advantages, CYGNSS can observe changes in soil moisture due to precipitation that may be too quick for the other satellites [e.g. NASA's Soil Moisture Active Passive] overpass period, thus further providing complete information on soil moisture dynamics (Chew and Small 2020).

For comparison, we have analysed the volumetric soil moisture (i.e. the content of liquid water in a surface soil layer of 2–5 cm depth) from the European Space Agency Climate Change Initiative (ESA CCI; Dorigo *et al* 2017, Gruber *et al* 2019) which are qualitatively similar to the results using CYGNSS soil moisture.

2.1.2. Precipitation

We use the precipitation from the Integrated Multi-satellitE Retrievals for Global Precipitation Measurement (IMERG) version 6 (Huffman *et al* 2019) to diagnose precipitation variability and to compare with the CYGNSS-derived soil moisture. Given the availability of the precipitation dataset, the IMERG Final Run product was used from January 2018 to September 2021, and the IMERG Late Run was used from October 2021 to December 2022.

2.1.3. Other datasets

To examine the impact of soil moisture on extreme climates, we have analysed several climate indices from the Copernicus Climate Change Service Climate Data Store (C3S CDS) and the European Centre for Medium-Range Weather Forecasts Reanalysis version 5 (ERA5):

- The McArthur Mark 5 Forest FDI (McArthur 1966, 1967, Noble *et al* 1980): measures the chances of a fire starting, its rate of spread, intensity, and its difficulty of suppression. The index is a combination of air temperature, relative humidity, wind speed, and long and short-term drought effects (C3S CDS 2019).

- The Keetch–Byram drought index (KBDI; Keetch and Byram 1968): refers to the net effect of evapotranspiration and precipitation in producing cumulative moisture deficiency, which can be calculated using the precipitation and maximum temperature input (C3S CDS 2019).
- To indicate flood risk, we analyse the river discharge from the Global Flood Awareness System (Harrigan *et al* 2021) and the surface runoff from the European Centre for Medium-Range Weather Forecasts Reanalysis version 5 (ERA5; Hersbach *et al* 2018, 2020).

2.2. Methods

2.2.1. Extreme soil moisture

While a better understanding of mean soil moisture would be of great value, the extremely high and low soil moisture are more relevant to weather and climate risks. To do this, we first sorted and binned all the data at each grid point according to soil moisture intensity with a total of 100 bins, i.e. each bin contains 1% of the total sampled soil moisture, similar to Bui *et al* (2019). Here, we consider two extreme cases where soil moisture is lower than the local 1st percentile and higher than the local 99th percentile (figure 1), similar to the criteria used by Wasko and Sharma (2017) and later by Sharma *et al* (2018). Note that the results shown here are not sensitive to which extreme criteria/threshold is used, and that our current results/conclusions are based on the 5 year data record of CYGNSS. We also examine the seasonal cycle of soil moisture by performing a Fourier transformation analysis on the daily time series to retain the first two harmonic cycles. The month, when extreme soil moisture occurs, is the month when the first maximum and minimum peak of soil moisture occurs in a year. In addition to estimating the extreme peaks by performing Fourier transformation on the daily data, we also average the daily data to the monthly mean. This alternative analysis using monthly mean helps smooth out day-to-day fluctuations to avoid more than two peaks when defining the maximum and minimum. However, the results of this monthly average are consistent with those derived from the Fourier analysis, so we only show the latter results here.

2.2.2. Linear regression models

To understand the impact of soil moisture on next-day precipitation, we estimate daily precipitation ($P_{\mathrm{day}-0}$) using two sets of multiple linear regression (MLR) models. The first model (or restricted model) predicts (or fits) precipitation occurrence with an independent variable that included past precipitation with sinusoids that vary in the seasonal timescales ($P_{\mathrm{day}-1}$) but not soil moisture:

$$P^{\mathrm{restricted}}_{\mathrm{day}-0} = a_1 \times P_{\mathrm{day}-1} + b_1. \qquad (1)$$

The second model (or full model) is the same as the restricted model but with soil moisture ($S_{\mathrm{day}-1}$) as an independent variable:

$$P^{\mathrm{full}}_{\mathrm{day}-0} = a_2 \times P_{\mathrm{day}-1} + b_2 \times S_{\mathrm{day}-1} + c \qquad (2)$$

where b_1, c are intercept, and a_1, a_2, b_2 are the regression coefficients derived from the MLR analysis that reflect the sensitivity of the dependent variable (i.e. predicted precipitation) to independent variables (i.e. yesterday's precipitation and yesterday's soil moisture).

In these two fitting (or predicting) regression models, we include the lagged precipitation ($P_{\mathrm{day}-1}$) to represent the persistence of precipitation affecting precipitation occurrence. Four days of lagged precipitation were added as independent variables originally, although only the first lag was found to be significant (see figure S1 in the supplementary material). Thus, only the first lag was used in the regression models shown here. The inclusion of lagged precipitation in the MLR directly accounts for the autocorrelation in precipitation issue, thus allowing us to examine the causal link between soil moisture and subsequent precipitation or the feedback of soil moisture on precipitation. These two regression models are closely related to the models Tuttle and Salvucci (2017) used, although we did not separate precipitation occurrence and magnitude. It is worth noting that while we did not perform a causality analysis (e.g. Granger causality) given the non-Gaussian fields, the results from MLR models do not change our conclusions about the feedback, as previously discussed by Tuttle and Salvucci (2017). However, we leave further exploration of the causality analysis to future work.

2.2.3. Quantification of soil moisture impact

To estimate the relative impact of soil moisture on predicted precipitation for each day in the 5 year study period, we divided the precipitation predicted by the full model by that of the restricted model, i.e. $P^{\mathrm{full}}_{\mathrm{day}-0}/P^{\mathrm{restricted}}_{\mathrm{day}-0}$. Note that only daily precipitation totals greater than 1 mm day^{-1} were considered to constitute an occurrence of precipitation on that day to avoid interpolation errors during the regression analysis. (Multiple threshold values for precipitation occurrence were tested, although it was found that the detected soil moisture-precipitation impact reached a plateau at a threshold of approximately 1 mm, consistent with previous study (Tuttle and Salvucci 2016)). Inspired by Tuttle and Salvucci (2016, 2017) we plotted this ratio quotient time-series against the anomalous (i.e. deseasonalized) daily soil moisture time-series at each grid point,

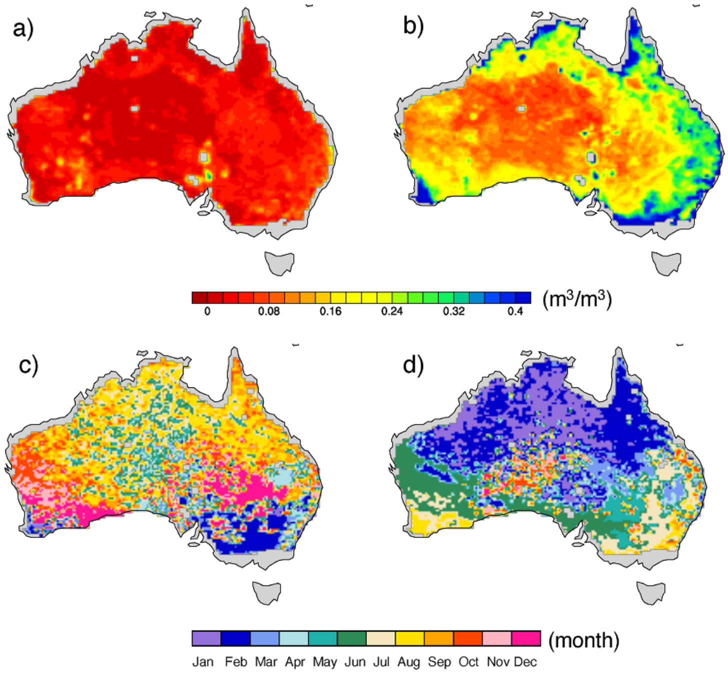

Figure 1. (a) and (b) Spatial distribution of (a) extremely dry (i.e. below the 1st percentile) and (b) extremely wet (i.e. above the 99th percentile) soil moisture from the CYGNSS (units are m^3/m^3). (c) and (d) The month when the extreme dry and wet soil moisture occurs, respectively. Shaded grey represents the missing data. The CYGNSS retrievals only provide data north of 38° S, so we lack data over the Victoria and Tasmania regions.

and the mean relative impact above and below the median soil moisture anomaly were calculated, similar to figure S3 in Tuttle and Salvucci (2016). This indicates the relative increase or decrease in precipitation due solely to soil moisture. To condense the information into a single measure of feedback strength and to examine the impact of dry and wet soil conditions, we also subtracted the mean of the below-median values from the mean of the above-median values of the anomalous daily soil moisture, which gives us a measure of the mean difference in the predicted precipitation between wet (above-median soil moisture) and dry (below-median soil moisture) periods as shown in figure 2. A positive value indicates positive soil moisture-precipitation feedback while a negative value indicates negative feedback. For reference, we show the differences of the means of the two models, i.e. $P^{\mathrm{full}}_{\mathrm{day}-0} - P^{\mathrm{restricted}}_{\mathrm{day}-0}$ in figure S2.

2.2.4. Consecutive dry and wet soil conditions

Finally, we examined how long the dry or wet soil conditions must persist before a drought, fire, or flood starts. The intensity of wet and dry soil moisture conditions is also considered. For example, a dry soil day is defined as when soil moisture is lower than the 5th, 10th, 15th, 20th, and 25th percentiles, while a wet soil day is when soil moisture is higher than the 75th, 80th, 85th, 90th, and 95th percentiles (figure 3). We normalized the fire and flood indices (see section 2.1.3) associated with the above soil moisture intensity by their average on all days (i.e. $\mathrm{FDI}_{\mathrm{dry\text{-}soil\text{-}day}}/\mathrm{FDI}_{\mathrm{mean}}$) to assess the impact of dry soil on wildfire probabilities and to find the number of consecutive days, similar to Bui *et al* (2022). Calculations are done at individual grid points and averaged over the northern Australia region (i.e. north of 18° S).

3. Results

3.1. Spatiotemporal distribution of extreme soil moisture

We first examine the spatiotemporal distribution of soil moisture, focusing on the extreme values where the soil moisture is wetter than (above) the local 99th percentile and drier than (below) the local 1st percentile (figure 1). The figure shows both spatial distribution and the month when the extreme values occur during the 5 year data record. The lowest soil moisture occurs over the western desert region, while the highest is near the north and southeastern coast (figures 1(a) and (b)). This variation is consistent with the spatial distribution of mean precipitation, which has its maximum over northern Australia and eastern coastal regions (King *et al* 2014). Unfortunately, the CYGNSS retrievals only provide data north of 38° S, so we lack data over the Victoria and Tasmania regions.

Soil moisture also exhibits a pronounced seasonal cycle in all regions, as shown in figures 1(c) and (d). The driest soil moisture peaks range from July to August in northern Australia (figure 1(c)), possibly related to lower temperatures and the minimum precipitation associated with the dry season.

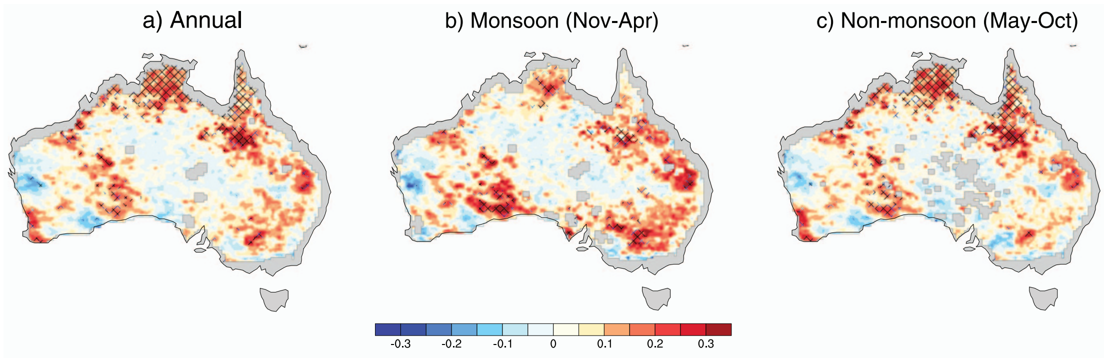

Figure 2. Maps showing soil moisture-precipitation feedback calculated from the multiple linear regression models (see section 2) for (a) annual, (b) monsoon season (November–April), and (c) non-monsoon season (May–October). Negative values mean the inclusion of soil moisture reduced the predicted precipitation intensity, while positive values indicate increased intensity. The strength of the feedback is a measure of the mean difference in the ratio of predicted precipitation from the models with and without soil moisture, between mean wet (above-median soil moisture anomaly) and dry (below-median soil moisture anomaly) conditions. Cross-hatching indicates the significant ($p < 0.1$) non-zero regression coefficient of the previous day's soil moisture (i.e. coefficient b2 in the full model). Shaded grey represents the missing data. The CYGNSS retrievals only provide data north of 38° S, so we lack data over the Victoria and Tasmania regions.

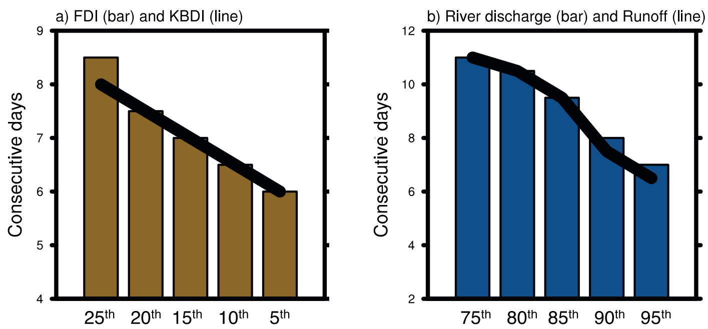

Figure 3. Consecutive days (y-axis, units are day) of soil moisture ranging from the 5th to 25th percentile (x-axis) preceding the maximum fire danger index (FDI, bar) and Keetch–Byram drought index (KBDI, line) averaged over the northern Australia (i.e. north of 18° S). (b) Similar to (a) but for the anomalous water discharge (bar) and runoff (line) when the soil moisture varies from 75th to 95th percentile.

Toward the south, the driest soil moisture occurs during December and January, except over the desert region in South Australia, where the minimum peak of soil moisture occurs around May–June. The wettest soil moisture peak generally occurs in January–February over northern Australia and occurs later as it moves further to the south (figure 1(d)). This latitude band pattern might be related to the movement of the intertropical convergence zone and monsoons. The months with maximum and minimum soil moisture are 6 months apart over most regions. We also note the consistency between CYGNSS and ESA CCI, although the peak seems to shift slightly in the CYGNSS, where both minimum and maximum peaks tend to occur earlier in the year (not shown).

3.2. Relationship between soil moisture and next-day precipitation

We further examine the relationship between soil moisture on one day and precipitation on the next day in Australia (figure 2). The impact of soil moisture on next-day precipitation was quantified by examining the differences between the full and restricted models (see section 2.2), which indicates the relative increase or decrease in precipitation intensity due solely to soil moisture. Figure 2(a) shows a clear connection between soil moisture and next-day precipitation in northern Australia, where wetter soil moisture leads to more precipitation on the next day. Notably, the feedback between soil moisture and next-day precipitation is not the same everywhere, implying different mechanisms for the feedback. The positive feedback is most robust across the central and northern Queensland and Northern Territory regions, with a confidence level of 90%. This result is consistent with moisture tracking analyses of Holgate *et al* (2020), who found that precipitation originating from a terrestrial source was greatest in northern Australia, where the strongest land-atmosphere coupling occurs. The feedback is also strong (although insignificant) in the eastern coastal regions, such as New South Wales and southeast Australia. Other regions, e.g. the southwest comer of Australia, show relatively small feedback because precipitation in this region was dominated by remote processes, in which it received most of its moisture from the ocean (figures 1(a) and (b)).

In addition to the regional dependence, the feedback between soil moisture and next-day precipitation might also vary with seasons. For example, during the monsoon months (November–April), precipitation is more likely to occur due to the long-term persistence of the monsoon over northern Australia, while during the non-monsoon period (May–October), the lack of moisture advection from the ocean could lead to decreased precipitation across the continent. To understand this seasonal dependence, we stratified the 5 year daily time series to monsoon and break periods. Based on this analysis, the positive feedback between soil moisture and next-day precipitation in northern Australia discussed above is closely associated with the break period (cf figures 2(a) and (c)). However, during the monsoon period, the positive feedback is strongest in the east-southeast regions (figure 2(b)). These feedback patterns are supported by the moisture recycling mechanism (Yu and Notaro 2020) that shows the terrestrial moisture source is strongest in north-northeast Australia in the austral winter (figure 2(c)) and weakest in the southwest during the austral summer (figure 2(b)). The shifted pattern of the feedback from the break to monsoon periods is also consistent with changes in mean and extreme precipitation and soil moisture due to tropical expansion (cf figures 2(b) and (c)). Notably, in southeast Australia, precipitation relies more on marine moisture, with the key regions being the Tasman Sea and Southern Ocean (Holgate *et al* 2020). Hence, the feedback between soil moisture and next-day precipitation is hard to define and deserves further analysis. Despite its simplicity, the application of the MLR approach to soil moisture-precipitation feedback shown in figure 2 has revealed more important details about the impacts of soil moisture on next-day precipitation in northern Australia during the non-monsoon period, which further implies the ability to constrain the intensity of next-day precipitation in these areas, independently of any precipitation persistence.

In addition to the linear regression analysis, we also examine the impact of soil moisture by calculating the conditional probability distribution function (PDF) of precipitation and previous-day soil moisture for a given precipitation history to examine the role of soil moisture (figure S3). The results are consistent with the feedback between soil moisture and next-day precipitation obtained from the MLR models, where drier soil is associated with a lower probability of next-day precipitation and vice versa. Another alternative approach is calculating the PDF, where predicted precipitation is binned based on the previous day's soil moisture (figure S4). In general, the conclusions from these PDF analyses are consistent with the regression models analysis even when the persistence of precipitation was included. In other words, our analysis indicates that conditioning on the states of soil moisture impacts the likelihood of next-day precipitation. The potential impacts of this soil moisture-precipitation relationship to the drought and flood conditions will be further examined below. However, we leave a detailed investigation of this behaviour to future modelling sensitivity studies where we can alternately test the increased or decreased past soil moisture.

3.3. Consecutive dry and wet soil moisture days

So far, we have examined the feedback between soil moisture and next-day precipitation; in this subsection, we shift our focus to the persistence and the intensity of soil moisture, which shows that the number of consecutive dry and wet soil days can further modulate wildfires and floods, a result that has implication on predicting extremes (figure 3). Figure 3(a) shows that the drier the soil, the fewer consecutive days are needed for the ratio of anomalous FDI to reach the highest value (i.e. higher chance of fire risk). This feature is consistently shown in the KBDI (black line in figure 3(a)). The increase in fire index can be explained by the drier soil moisture that dries out fuels and thus supports combustion. Note that soil moisture is not included in the calculation of FDI and KBDI, therefore giving us an objective evaluation of how soil moisture impacts these indices. In other words, soil moisture is proportional to the time before fire ignition, and we can use soil moisture deficit as an indicator of wildfire risk. Notably, in a tropical climate region like northern Australia, the magnitude of the dry soil moisture before the fire is greater than in arid regions, and since moisture is mostly not limiting and therefore only weakly controlling fire dynamics in a wet region. The longer the preceding period of dry-soil days, the higher the fire danger and drought indices, consistent with previous work that argued that the persistence of high pressure could dry out the soil in addition to the dryness caused by intense evaporation due to fire exposure (Bui *et al* 2022). However, given the complication of fire in the climate system, more work is needed to understand the relationship between soil moisture and wildfire occurrence, in particular, how global-scale modes of atmospheric variability modulate this relationship, including teleconnections.

We repeat the above soil moisture analysis for flood risk, considering a wet soil situation (i.e. above the 75th percentile). As shown in figure 3(b), the wetter the soil moisture, the higher the probability of flooding. This result is consistent with previous studies about the linkage between flood timing and soil moisture amount (Berghuijs *et al* 2019) and the modulation of flood magnitude by antecedent soil moisture (Wasko *et al* 2020). However, understanding the impact of floods on soil moisture is difficult due to, for example, the coupling of floods to soil moisture and rainfall behaviour. Although changes in both soil moisture and extreme rainfall can influence floods, the more extreme flood events are less dependent on soil moisture changes (Wasko and Nathan 2019). In other words, there may be a tipping point in severity where changes in soil moisture no longer have a dominant influence on the resulting changes in streamflow, as reported in the previous study (Wasko *et al* 2020) that for less extreme events, flood is more likely correspond to soil moisture whereas rainfall becomes increasingly important as flood severity increases. Regardless, the results help to search for potential flood initiation by a constraint soil moisture, which is a great challenge in extreme weather management.

4. Concluding remarks

We analysed the recently launched CYGNSS dataset to examine the relationship between soil moisture variability and precipitation over Australia. The results from the current 5 year data record showed the spatiotemporal distribution of extreme soil moisture, where the highest soil moisture occurred over eastern Australia and the lowest over western Australia. MLR analysis demonstrated that soil moisture anomalies influence next-day precipitation, such that higher soil moisture is associated with a higher precipitation intensity and vice versa, even when the persistence of precipitation was considered. We found significantly strong and positive feedback between soil moisture and next-day precipitation in northern Australia during the non-monsoon period, possibly due to strong land-atmosphere coupling and the dominated terrestrial moisture source in this region. Soil moisture-precipitation feedback is not significant over much of other regions across Australia, including the southeast coastal area, where precipitation depends more on marine moisture. Further analysis of the persistence of dry and wet soil conditions showed drastic increases in drought, fire, and flood probabilities, respectively, implying that soil moisture is a good indicator of extreme risks. These results—based on novel data blending satellite retrievals and remote sensing—provide new insights into Australian soil moisture that had not been previously quantified, thus guiding future research into soil moisture mechanisms that influence extreme weather and climate.

Although the current results reveal several interesting facts regarding the impacts of soil moisture on next-day precipitation in Australia, there are a few caveats to consider. The soil moisture feedback is dependent on satellite precipitation data quality and incurs the attendant errors and biases, and we emphasize that the results of this current analysis only reflect soil moisture-precipitation feedback at a daily time-step and 0.5° spatial resolution. We note that soil moisture and precipitation feedback might vary on sub-daily timescales, while our analysis reflects soil moisture-precipitation feedback at a daily time-step that is independent of the time of day. Assessing the feedback as a function of time of day would be valuable, and we refer this to future work given the current data record of CYGNSS. We also did not include other meteorological information in the study besides precipitation. The impacts of these climate variables (e.g. humidity, wind, etc) on soil moisture feedback are worthy of analysis, although they are separate from the aims of this study. Finally, given the current short-term 5 year record of CYGNSS, we did not study the interaction between soil moisture and next-day precipitation and ENSO or Indian Ocean Dipole (IOD) events, which are known to affect the precipitation variation in Australia. In our 5 year data, there is an El Niño (2018), three La Niña (2020–2022), and a positive IOD (2019). The impact of these climate modes on soil moisture feedback is a worthy analysis separate from this study. Despite these caveats, the geographic distribution of extreme soil moisture and the feedback between soil moisture and next-day precipitation shown above give us confidence in the robustness of our conclusions about the feedback between soil moisture and next-day precipitation in Australia. These results also suggest that extreme events can be linked to land-atmosphere interactions that may afford opportunities to improve extreme forecasts.

The current study is only a first step in assessing the influence of soil moisture on weather and climate extremes. We note that the impacts of soil moisture on precipitation can vary on different timescales and time lags (e.g. Findell and Eltahir 1997, Dirmeyer *et al* 2009, Mei and Wang 2012), and our results provide another datapoint on how soil moisture on one day influence on precipitation on the next day in Australia. Given the complex interaction between the atmosphere and land-surface processes, this analysis does not identify a specific mechanism for soil moisture-precipitation feedback. Also, given the multitude of potential fire and flood drivers, separating the role of soil moisture can be challenging. With increased coverage and the ability to measure in regions of heavy rainfall, CYGNSS provides insights into soil moisture processes that do not rely on the assumptions inherent in reanalysis data. Since the current results are based on five years of CYGNSS data (2018–2022), it is critical to re-examine the robustness of the results derived here as a longer CYGNSS data record becomes available and as new versions of CYGNSS products with improved algorithms are developed. Regardless, a robust conclusion from our current study is that there is a coherent relationship between soil moisture and next-day precipitation and the likelihood of extreme events. Future modelling work would be required to understand this relationship further.

Data availability statements

CYGNSS soil moisture can be downloaded at https://doi.org/10.5067/CYGNU-L3SM1. GPM precipitation can be downloaded at https://dx.doi.org/10.5067/GPM/IMERGDF/DAY/06. River discharge from the Global Flood Awareness System (GloFAS) is available at https://doi.org/10.24381/cds.a4fdd6b9. Fire danger index data from the Copernicus Emergency Management Service at https://doi.org/10.24381/cds.0e89c522.

All data that support the findings of this study are included within the article (and any supplementary files).

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