Seesaw terrestrial wetting and drying between eastern and western Australia

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Abstract

Australia, the driest inhabited continent, is prone to natural disasters, such as droughts, floods, bushfires and heatwaves. Strong climate variability causes regular threats to water supply, agriculture and the environment. Improving our insight into changes in hydroclimatic patterns is required to provide useful information for society. Previous studies mainly focused on the causes of extreme wet or dry events in specific periods and their impacts on agriculture and ecosystems. An understanding of long-term spatio-temporal patterns of wetting and drying in Australia is still lacking. Here we show, based on analyses of GRACE satellite derived terrestrial water storage (*TWS*) and extended datasets, that there are four continuous periods of seesaw wetting and drying between eastern and western Australia in the past five decades. The seesaw phenomenon is characterized by eastern Australia gaining water, while western Australia is losing water, and vice versa. Strong *La Niña* induced continent-wide wetting, resets this pattern, leaving each seesaw to last for 11 ± 5 years. We provide one possible mechanism related to vegetation response to climate variability and its feedback on hydrological processes to explain the seesaw resetting pattern. The identified reoccurring seesaw pattern indicates that society would need to become more adaptive in managing forest, water, and disaster risks in the wake of a next strong *La Niña* induced continent-wide wetting in Australia.

Significance Statement

Large-scale wetting/drying in Australia is commonly thought to be controlled by precipitation. Here we report for the first time a vegetation mediated seesaw wetting/drying phenomenon between eastern and western Australia. The seesaw phenomenon is characterized by eastern Australia gaining water, while western Australia is losing water, and vice versa. It is reset by strong *La Niña* induced continent-wide wetting. The seesaw phase seems dependent on vegetation cover anomaly prior to the strong *La Niña* event, and can be explained by subsequent vegetation and soil moisture interactions. This finding provides society with valuable reference for managing forest, water, and disaster risks in the wake of a next strong *La Niña* induced continent-wide wetting in Australia.

Introduction

Australia is the driest inhabited continent on Earth and among the areas of the most variable rainfall in the world (1, 2). Its hydroclimatic variations play an important role in the global carbon and water cycles (3, 4), occurrence of natural hazards (5, 6), and agricultural productivity (7). Droughts occurring in Australia during 2000-2009 were reported to reduce global terrestrial net primary production (8). Poulter et al. (9) indicated that the global land carbon sink anomaly triggered by the 2010-11 *La Niña* event was largely due to an enhanced ecosystem productivity across the Southern Hemisphere, particularly in Australia. Frequent droughts cause agricultural losses (10, 11), contribute to bushfires (12) and exacerbate heatwaves (13, 14), and consequently impact the economy and society significantly (11). This continent is also prone to floods, which lead to serious

casualties and economic losses (5). Hence, furthering our understanding and monitoring of wet and dry conditions in Australia is urgently needed for water, agriculture, and disaster risk management.

Previous studies mainly focused on the causes of droughts or floods in discrete periods and their impacts on ecosystems and society (5, 6, 11, 15, 16). Xie et al. (4) recently investigated the wet and dry evolution across continental Australia based on Gravity Recovery and Climate Experiment (GRACE) terrestrial water storage (*TWS*) dataset (2002-2014). They revealed three geographic zones with distinct *TWS* responses and attributed them to different large-scale teleconnections. If such regional differentiated *TWS* responses hold over a long period, it would provide society useful information for climate-adaptive water resource planning and management. In this study, we aim to reveal long-term spatio-temporal patterns of *TWS* in Australia, and to examine how these patterns are associated with climate variability and land surface processes.

Results and discussion

Main spatial patterns of *TWS* variation in Australia

The space-time fields of monthly Australia *TWS* anomaly from three datasets (14-year original JPL GRACE *TWS* (17, 18) and reconstructed GRACE *TWS* of 31 (19) and 114 years (20) have been decomposed by empirical orthogonal functions (EOFs). We focus on the first two modes since they explain more than 50% of the total variance. The three datasets exhibit similar spatial patterns (Fig. 1). Almost all grid cells (more than 90%) show consistent phase in terms of spatial pattern *EOF1* (Fig. 1 (a) (c) (e)) indicating that the wet and dry alternation has consistency over the whole continent, although the north and east parts have higher variability. This EOF mode explains more than 30% of the total *TWS* variability in Australia. The spatial pattern *EOF2* clearly delineates two zones, eastern and western Australia, with opposite behavior (Fig. 1 (b) (d) (f)). This mode is defined as an east-west opposite pattern, which explains around 20% of the total variation of the *TWS* anomaly in Australia. The dashed line in Fig. 1 is drawn based on the average results from the three datasets of different year ranges. This line is coincident with the boundary of the western plateaus and central plains of the Australian continent.

Four consecutive seesaw wetting and drying phases between eastern and western Australia in the past five decades

The temporal signal of the first decomposed mode (*PC1*) reflects the wet (positive *PC1*) and dry (negative *PC1*) conditions in terms of average *TWS* anomaly over the whole continent. The continent-wide wetting and drying are closely related to large-scale ocean-atmosphere dynamics. As shown in Fig. 2, continent-wide wetting episodes represented by positive phases of *PC1* generally correspond to positive phases of *SOI* (*La Niña* episodes). We use pairs of dashed lines to mark the *La Niña* induced continent-wide wetting episodes, which are bounded by the time points when average *TWS* anomaly in Australia starts to increase, triggered by strong *La Niña*, and when it returns to equilibrium. Nine *La Niña* induced continent-wide wetting episodes are identified during 1901-2014 (W1: Dec 1903-Jan 1905, W2: Mar 1910-Feb 1911, W3: Nov 1916-Nov 1918, W4: Dec 1949-Nov 1951, W5: Feb 1956-Dec 1957, W6: Jul 1973-Mar 1980, W7: Apr 1989-Sep 1989, W8: Aug 1998-Jun 2002, W9: Apr 2010- Jan 2013, see Fig. 2 (a)). As this 114-year reconstructed GRACE *TWS* dataset is the mean of 100 ensemble members, uncertainty in *PC1* is quantified by ± 1 standard deviation of 100 *PC1* time series derived from the ensemble members (Fig. 2 (a)).

As the eastern and western parts of Australia have opposite phases in *EOF2* (Fig. 1 (b) (d) (f)), they are supposed to behave oppositely in terms of *TWS* variation. The periods in-between the *La Niña* induced

continent-wide wetting episodes, show piece-wise linear trends of the regional average *TWS* anomaly in the eastern and western parts of Australia (Fig. 3 (a)). Four consecutive opposite *TWS* trends between eastern and western Australia are observed during the past five decades (1958-2010). In those four consecutive interval periods, changes of regional average *TWS* anomaly between the two parts are significantly different at 0.05 significance level (tested by analysis of covariance). This phenomenon is identified as seesaw wetting and drying between these two geographical parts of Australia. The seesaw is characterized by eastern Australia gaining (losing) water, while the west is losing (gaining) water. It appears that a seesaw is reset by a continent-wide wetting episode, turning an earlier wetting (drying) side to lose (gain) water. Another seesaw phenomenon is observed during the 1910s. These five seesaw periods last for 11 ± 5 years. Uncertainty in regional average *TWS* time series is represented by the shaded area in Fig. 3 (a). Uncertainty of the consecutive opposite trends in the last four interval periods is quantified in Fig. 3 (b), the average linear trends of the east and west part derived from 100 ensemble members are significantly different at 0.05 significance level.

Input data of both models for reconstructing the 31- and 114-year *TWS* include precipitation and temperature information. Data of those two climate variables are of low quality for most of the 114-year time series. Therefore, we repeated above analysis with the 31-year reconstructed *TWS* data (1985-2015) for comparison. Three *La Niña* induced continent-wide wetting episodes (Apr 1989-Jan 1990, Aug 1998-Jun 2002, and Aug 2010- Feb 2013) are marked in Fig. 2 (b), which respectively correspond to W7-9 shown in Fig. 2 (a), although minor differences exist. The regional average *TWS* anomaly of the eastern and western parts of Australia from 1985 to 2015 are plotted in Fig. 3 (c). Two pairs of opposite trends (all are significant at 0.05 significance level) are observed in the interval periods which correspond to the last two seesaws shown in Fig. 3 (a) respectively.

No seesaw phenomenon is observed if the interval between two *La Niña* induced continent-wide wetting episodes is too short (1905-1910) or too long (1918-1949). A positive Interdecadal Pacific Oscillation (*IPO*) phase dominated during 1922-1944 (21), which may have suppressed the occurrence of a *La Niña* event and/or moderate the *La Niña* effect (22-26). Indeed, from 1918 to 1949, only one moderate *La Niña* occurred (1938-1939), but it did not induce continent-wide wetting (Fig. 2 (a)). The length of a continent-wide wetting episode (reflected in the *PC1* response, Fig. 2) appears to be associated with the intensity and duration of the *La Niña* events, as well as the conjunction effects from other oscillations. The wetting episode W7 is short (10 months), which is likely due to the modulation effect of the positive *IPO* phase (1978-1998) (21). Different from the situation in the previous positive *IPO* (1922-1944), the *La Niña* in W7 is strong enough to lead to a continent-wide wetting and reset the seesaw between eastern and western Australia. Here, the *La Niña* coincident with a negative Indian Ocean Dipole (*IOD*) (Fig. S1) may explain this situation. Negative *IOD* usually enhances a *La Niña* effect, it can also lead to a wetter than normal condition in western and southern Australia (27, 28).

Independent evidence for *TWS* seesaw between eastern and western Australia

A soil moisture dataset for 1901-2014 provided by Australian Water Availability Project (AWAP) (29, 30) also shows a seesaw pattern (Fig. S2 (a)) consistent with that of *TWS* shown in Fig. 3 (a). The agreement between the results based on two independent data sources supports the validity of the *TWS* seesaw between the two parts of Australia, because changes in soil moisture are typically the largest component of terrestrial water storage variation (31).

In addition, as ecosystems are mostly water limited in Australia, changes of terrestrial water storage should have led to and be reflected in vegetation responses. Global Inventory Monitoring and Modeling System (GIMMS) Normalized Difference Vegetation Index (*NDVI*) data is available from July 1981 to 2015, which provides an opportunity to verify the most recent two *TWS* seesaw phenomena (Feb 1990-Jul 1998 and Jul 2002-Jul 2010, following the intervals identified based on 31-year reconstructed *TWS* data). Linear *NDVI* trends during those two seesaws at each grid cell are shown in Fig. 4 (a) and (b) respectively. A marked east-west difference in *NDVI* trends can be observed for both periods. During Feb 1990-Jul 1998, *NDVI* anomaly increases in the western region and decreases in the eastern region of Australia (Fig. 4 (a)), which is consistent with *TWS* wetting in the west and drying in the east (Fig. 3 (c)). During Jul 2002-Jul 2010, *NDVI* anomaly (Fig. 4 (b)) also shows consistent trends with *TWS* (Fig. 3 (c)). Similar to Fig. 3 (c), we plot the regional average *NDVI* anomaly of eastern and western Australia from 1985 to 2015 in Fig. 4 (c). During the interval between W7 and W8, the regional average *NDVI* anomaly significantly increases in the west and slightly decreases in the east. During the interval between W8 and W9, average *NDVI* anomaly significantly increases in the east and slightly decreases in the west. Changes of regional average *NDVI* anomaly between the two parts are significantly different in both interval periods (Fig. 4 (c)). These *NDVI* seesaws, consistent with those of *TWS* ones, between the western and eastern parts of Australia, provide strong support for the seesaw pattern of *TWS* variation in Australia.

Possible mechanism of the Australia *TWS* seesaw phenomenon

For the four consecutive *TWS* seesaws between eastern and western Australia, the seesaw state seems to be reset by a continent-wide wetting episode. In other words, if a region was gaining water before the wetting episode, it would be losing water after that. Since terrestrial water storage is mainly recharged by precipitation, we attempted to explain the seesaw phenomenon of *TWS* by looking into precipitation patterns. The regional average precipitation (provided by AWAP) in the eastern and western parts of Australia during 1901-2014 is plotted in Fig. S2 (b). Opposite trends between two parts are shown for the last three intervals, however, most of them do not pass the significance test at 0.05 significance level. Thus, large-scale precipitation variability, likely associated with climate teleconnections, cannot explain the four consecutive *TWS* seesaws.

Here we provide one possible mechanism related to dynamic woody vegetation and soil moisture interactions, which appears to explain the seesaw resetting pattern (Fig. 5). For a region with an increasing *TWS* (the lower blue arrow in Fig. 5) during a seesaw period, vegetation cover tends to be well developed prior to a wetting episode. Such an improved vegetation cover makes the region to have a larger than normal storm water retention capacity for big wetting events, e.g., by root enhanced infiltration and organic matter facilitated soil hydrophilicity (32-34). Following the wetting episode, this increasing vegetation cover tends to demand more root water uptake, which gradually depletes soil moisture, and thus *TWS* (the upper blue arrow in Fig. 5). This process reverses the previous positive *TWS* trend to a negative one.

In contrast, for a region with a decreasing *TWS* (the upper blue arrow in Fig. 5) during a seesaw period, vegetation cover will reduce. Such a surface tends to favor runoff generation and soil erosion, leading to a lower storm water retention (35-37). Since Australia is prone to wildfires, the storm water retention can be further weakened by fire-induced hydrophobic soils (38). After the wetting episode, the previously reduced vegetation cover demands less soil moisture, leading to a gradual increase of *TWS* (the lower blue arrow in Fig. 5) during the interval period.

The above two situations explain the seesaw resetting pattern in which a positive (negative) seesaw stage is reset to a negative (positive) one after a short wetting episode. In the last three interval periods precipitation shows opposite trends between the eastern and western parts of Australia consistent with *TWS*, vegetation recovering (degrading) might be facilitated by increasing (decreasing) precipitation. However, no significant difference of changes in regional average precipitation anomaly between eastern and western Australia is observed in any interval period (Fig. S2 (b)). It suggests that vegetation and soil moisture interactions are very likely the primary mechanism for the observed *TWS* seesaws.

By comparing the 12-month average *NDVI* anomaly immediately before (Fig. 6 (a-c)) and 12-month average *TWS* anomaly immediately after (Fig. 6 (d-f)) the three *La Niña* induced continent-wide wetting episodes shown in Fig. 2 (b), we can see that the half of the continent (either east or west) with increased vegetation cover (positive *NDVI* anomaly) prior to a *La Niña* triggered wetting episode, retains larger than normal storm water (positive *TWS* anomaly) after the episode. After a wetting episode, the part dominated by positive *NDVI* and *TWS* anomalies experiences a decreasing evapotranspiration (*ET*) (Fig. 6 (g-h)), reflecting a gradually decreasing vegetation cover resulting from a depleting *TWS*. These processes are consistent with the trends of *NDVI* and *TWS* during the corresponding interval period. In addition, vegetation in the region with positive (negative) *NDVI* anomaly prior to the last *La Niña* induced continent-wide wetting shows decreasing (increasing) trend during Mar 2013-Dec 2018 (Fig. S3). Such results support the mechanism of the Australia *TWS* seesaw phenomenon we explained above.

Based on this understanding, we suppose that vegetation dynamic, in response to continent-wide wetting, plays an important role in the *TWS* seesaw in Australia. However, the interval period should be long enough for woody vegetation to recover in one part while to degrade in the other part of Australia, so that *TWS* seesaw between the two parts could be reset by a *La Niña* induced continent-wide wetting.

Conclusion

This study, based on three *TWS* datasets (14-year original JPL GRACE *TWS* and 31- and 114-year reconstructed GRACE *TWS*), elucidates a new spatio-temporal pattern of wetting-drying over Australia. Four continuous seesaw wetting and drying phases between eastern and western Australia are observed in the past five decades, which is characterized by eastern Australia gaining water while the western part is losing water, and vice versa. Strong *La Niña* induced continent-wide wetting, resets this pattern, leaving each seesaw to last for 11 ± 5 years. The *TWS* seesaw phenomenon is substantiated by a similar pattern in *NDVI* between eastern and western Australia during Feb 1990-Jul 1998 and Jul 2002-Jul 2010. This continental scale *TWS* seesaw pattern seems to be resulting from woody vegetation response to climate variability and its feedback on hydrological processes.

The results of this study contribute to a better understanding of drying and wetting phases and hence can stimulate an adaptive forest, water, and disaster risk management in the wake of a strong *La Niña* induced continent-wide wetting in Australia. Our finding suggests that at the end of a seesaw drying phase, poor vegetation cover limits the landscape water retention capacity. Hence, during a drying phase a reasonable management response might be to increase storm water harvesting capacity. At the beginning of a seesaw drying phase, previously increased vegetation cover (resulting from a previous seesaw wetting) depletes root zone moisture, leading to landscape degradation in the subsequent years. Reducing vegetation cover right after the wetting episode might reduce the risk of heatwaves and bushfires in the later dry stage.

Materials and Methods

Datasets. Three *TWS* datasets are applied in this study. The first is the original GRACE *TWS* dataset (RL06M.MSCNV01) (17, 18) from 2003 to 2016 provided by the NASA Jet Propulsion Laboratory (JPL). Seventeen months of missing *TWS* data (June 2003, January 2011, June 2011, May 2012, October 2012, March 2013, August 2013, September 2013, February 2014, July 2014, December 2014, June 2015, October 2015, November 2015, April 2016, September 2016 and October 2016) are filled by linear interpolation using the months either side (39, 40). In order to investigate the wetting and drying cycles over a long period, two reconstructed GRACE *TWS* datasets for 1985-2015 (19) and for 1901-2014 (20) are also applied. Statistical data-driven models, calibrated with observations, are used to reconstruct the *TWS* dataset of 1901-2014, which perform well compared with state-of-the-art hydrological models (20, 41). The seasonality of *TWS* has been removed, which is represented by the use of a *TWS* anomaly in this study. GIMMS *NDVI* dataset (42, 43) is available from July 1981 to December 2015. Moderate Resolution Imaging Spectroradiometer (MODIS) *NDVI* dataset (44) is available from March 2000. Both *TWS* and *NDVI* data are used at a $0.5^\circ \times 0.5^\circ$ spatial resolution. GLDAS_NOAH025_M evapotranspiration data (45, 46) are used at a $0.25^\circ \times 0.25^\circ$ spatial resolution. AWAP soil moisture and precipitation data (29, 30) are of $0.05^\circ \times 0.05^\circ$ spatial resolution.

Climate indices. Two ocean-atmosphere indices including Southern Oscillation Index (*SOI*) (47-49) and Indian Ocean Dipole Mode Index (*DMI*) (50) are applied in this study since they play an important role in Australia's hydroclimatic variations (11, 15, 51).

EOFs. The empirical orthogonal functions (EOFs) decompose a space-time field into spatial patterns and associated temporal signals. For a continuous space-time field *TWS* (t, s), t and s denote respectively time and spatial position, the decomposition is described as in the study of Hannachi et al. (52):

$$TWS(t, s) = \sum_{k=1}^K c_k(t) u_k(s) \quad (1)$$

where K is the number of modes included in the field, using an optimal set of basis functions of space $u_k(s)$ and expansion functions of time $c_k(t)$. For the space-time field of *TWS* over Australia, the EOFs method finds a set of orthogonal spatial patterns (EOF_k) along with a set of associated uncorrelated time series or principal components (PC_k) (i.e., $PC1$ corresponds to $EOF1$ and so on). This method also provides the explained variance, which indicates how much variability of *TWS* is explained by each decomposed mode (EOF_k/PC_k).

Significance test. The significance of linear trend is tested by the Mann-Kendall (M-K) test (53, 54). Analysis of covariance is applied to test the significance of difference between two time series. The 0.05 significance level is adopted in this study.

Acknowledgments

The datasets used in this study are available online in the following locations: JPL GRACE *TWS*, <https://grace.jpl.nasa.gov/>; reconstructed *TWS* from 1985-2015 (GRACE_REC_v01), http://rossa-prod-ap21.ethz.ch/delivery/DeliveryManagerServlet?dps_pid=IE5766472; reconstructed *TWS* from 1901-2014 (GRACE_REC_v03), <https://doi.org/10.6084/m9.figshare.7670849>; GIMMS *NDVI*, <https://climatedataguide.ucar.edu/climate-data/ndvi-normalized-difference-vegetation-index-3rd-generation-nasagfsc-gimms>; MODIS *NDVI*, https://neo.sci.gsfc.nasa.gov/view.php?datasetId=MOD_NDVI_M; GLDAS_NOAH *ET*,

https://disc.gsfc.nasa.gov/datasets/GLDAS_NOAH025_M_2.0/summary?keywords=GLDAS; SOI index, https://www.esrl.noaa.gov/psd/gcos_wgsp/Timeseries/SOI/; DMI index, https://www.esrl.noaa.gov/psd/gcos_wgsp/Timeseries/DMI/. AWAP soil moisture and precipitation data are viewable at: <http://www.csiro.au/awap> and downloadable via ftp by application to Peter.Briggs@csiro.au. We are thankful to their provision of data. The first author's PhD scholarship has been provided by the China Scholarship Council, Ministry of Education, China, and Flinders University, Australia.

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Figures and Tables

Figure 1. Spatial patterns of the first two modes (*EOF1* & *EOF2*) of Australia *TWS* variation. (A-B) 14-year original JPL GRACE *TWS* (2003-2016), (C-D) 31-year reconstructed GRACE *TWS* (1985-2015), (E-F) 114-year reconstructed GRACE *TWS* (1901-2014). Acronym “ev” stands for explained variance. An east-west opposite (*EOF2*) pattern is observed in all three datasets.

Figure 2. *La Niña* induced continent-wide wetting episodes identified based on *SOI* and the temporal signal of the first mode (*PC1*) of Australia *TWS* variation. (A) *PC1* vs. *SOI* during 1901-2014 ($r=0.18$, $p<0.05$). The black curve indicates mean *PC1* derived from 100 *PC1* members and the shaded areas represent ± 1 standard deviation of 100 *PC1* time series derived from the ensemble members. A 3-month moving average was applied to *SOI* for readability (orange curve). The periods marked by a pair of dashed lines denote the *La Niña* (positive *SOI*) induced continent-wide wetting episodes (positive *PC1*) (W1: Dec 1903-Jan 1905, W2: Mar 1910-Feb 1911, W3: Nov 1916-Nov 1918, W4: Dec 1949-Nov 1951, W5: Feb 1956-Dec 1957, W6: Jul 1973-Mar 1980, W7: Apr 1989-Sep 1989, W8: Aug 1998-Jun 2002, W9: Apr 2010- Jan 2013), which are identified according to the time points when average *TWS* anomaly in Australia starts to increase, triggered by strong *La Niña*, and when it returns to equilibrium. (B) *PC1* vs. *SOI* during 1985-2015 ($r=0.23$, $p<0.05$). The three marked *La Niña* induced continent-wide wetting episodes (Apr 1989-Jan 1990, Aug 1998-Jun 2002, and Aug 2010- Feb 2013) respectively correspond to W7, W8 and W9 shown in (A).

Figure 3. TWS seesaw between eastern and western Australia. (A) Regional average TWS anomaly of eastern and western Australia during 1901-2014 (the boundary of eastern and western parts is shown in Fig. 1). Uncertainty (shaded area) is quantified by ± 1 standard deviation derived from 100 ensemble members. Opposite linear trends of regional average TWS anomaly of eastern and western Australia are observed for Mar 1911-Oct 1916, Jan 1958-Jun 1973, Apr 1980-Mar 1989, Oct 1989-Jul 1998 and Jul 2002-Mar 2010 (blue (red) asterisk (*) indicates the trend of eastern (western) Australia is significant at 0.05 significance level, and the black asterisk indicates the changes of regional average TWS anomaly between eastern and western Australia are significantly different); (B) slopes of regional average TWS anomaly derived from 100 ensemble members in the last four interval periods (5~8). Hatched bars indicate uncertainty (± 1 standard deviation) in trends. Within all the four interval periods, average trends of the East and West part are significantly different at 0.05 significance level. (C) same as (A) but based on TWS data of 1985-2015. Opposite linear trends of regional average TWS anomaly of the East and West part are observed during Feb 1990-Jul 1998 and Jul 2002- Jul 2010.

Figure 4. Seesaw phenomenon of *NDVI* during 1985-2015. (A-B) Linear trends (per month) of *NDVI* during two interval periods (Feb 1990-Jul 1998 and Jul 2002- Jul 2010); (C) same as Fig. 3 (C) but for *NDVI* anomaly. Opposite linear trends of regional average *NDVI* anomaly of eastern and western Australia are observed during Feb 1990-Jul 1998 and Jul 2002- Jul 2010. Two upward trends are significant at 0.05 significance level while two downward trends are non-significant. Changes of regional average *NDVI* anomaly between the two parts are significantly different in both interval periods.

Figure 5. A schematic showing possible terrestrial water storage and vegetation interactions, leading to *TWS* seesaw and its resetting by big wetting episodes.

Figure 6. Evidence for the possible mechanism of the *TWS* seesaw phenomenon. Average 12-month *NDVI* anomaly (A-C) immediately before and average 12-month *TWS* anomaly (D-F) immediately after the three continent-wide wetting episodes: Apr 1989-Jan 1990, Aug 1998-Jun 2002, and Aug 2010- Feb 2013; (G-H) linear trends of evapotranspiration (*ET*) during two interval periods: Feb 1990-Jul 1998 and Jul 2002- Jul 2010.

Fig. S1. Plot of *PC1*, monthly *SOI* and *DMI* from 1985 to 1995.

Fig. S2. (A) Regional average soil moisture of eastern and western Australia during 1901-2014, which shows a similar seesaw pattern to *TWS* (changes of regional average soil moisture between eastern and western Australia are significantly different in five interval periods: Mar 1911-Oct 1916, Jan 1958-Jun 1973, Apr 1980-Mar 1989, Oct 1989-Jul 1998 and Aug 2002-Mar 2010; (B) same as (A) but for precipitation, opposite trends are observed in the last three interval periods, but no significant difference of changes in regional average precipitation anomaly between eastern and western Australia is observed in any interval period.

Fig. S3. (A-B) Linear trends (per month) of MODIS *NDVI* during Jul 2002-Jul 2010 and Mar 2013-Dec 2018; (C) regional average *NDVI* anomaly of eastern and western Australia during 2001-2018. Results from GIMMS (Fig. 4) and MODIS *NDVI* datasets are consistent during the overlapped interval Jul 2002-Jul 2010. Opposite linear trends between the two parts are also observed during Mar 2013-Dec 2018. Changes of regional average MODIS *NDVI* anomaly between eastern and western Australia are significantly different in both interval periods.