Evaluating land use change impacts on rainfall in various categories using the Weather Research and Forecasting-mosaic approach

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Funding information
National Key R&D Program of China, Grant/Award Number: 2016YFA0600403; National Natural Science Foundation of China, Grant/Award Number: 41775087 and 41675149; National Key Basic Research Program on Global Change, Grant/Award Number: 2011CB952003; Jiangsu Collaborative Innovation Center for Climatic Change

To evaluate land use change impacts on rainfall in various categories, satellite-based images representing land use change between 1980 and 2010 were adopted to perform numerical experiments using the Weather Research and Forecasting regional climate model. The mosaic approach, rather than the dominant approach, was employed to describe the land surface characteristics and their corresponding changes, for which the changes in the land surface physical parameters were closer to the actual values. Changes in rainfall displayed marked subregional characteristics, which could be interpreted by changes in local upward and large-scale moisture fluxes. Meanwhile, changes in the total rainfall (RCN) in various categories displayed remarkably different characteristics. Among these characteristics, storm and heavy storm rain expressed larger changes (relative values) and displayed stronger sensitivities over semi-arid subregions. Storm and heavy storm rainfall increased up to 10.5% in the eastern part of northwestern China (NWE) and 13.6% over northeastern China and decreased up to 6.5% over the Tibetan Plateau and 11.9% over NWE. According to changes in the convective (RC) and non-convective (RN) rainfall, the RCN for both storm and heavy storm rain were influenced by changes not only in the RC, RN, and RCN intensities, but also in the rain areas and number of rain days. The impacts of land use change on the summed RC, RN, and RCN for various categories might be less, whereas changes in the RC, RN, and RCN for individual various categories could be much larger. The rainfall impacts in various categories were higher over the subregions of China compared to China overall or the East Asian land areas, and those impacts demonstrated smaller influences at the regional scale (country-wide, China) compared to the local scale (subregions of China). Therefore, the impacts of land use change on rainfall in various categories are important for climatic change studies.

KEYWORDS
land use change, mosaic approach, rain areas and number of rain days, rainfall intensity, storm and heavy storm rain

1 | INTRODUCTION

Floods are usually associated with strong rainfall. Strong annual rainfall frequencies and intensities, which express marked subregional characteristics in China, have changed under global warming (Liu, 1999; Shi et al., 2002; Wang et al., 2007; Zhang et al., 2008; Gao and Xie, 2014). These changes can be attributed to the natural variability in the climate system and the impacts of various anthropogenic activities, including greenhouse gas emissions, aerosol emissions,
and land use change (IPCC, 2013). Among these impacts, those of land use change on rainfall in various categories, especially for storm and heavy storm rain, are the focus of this study.

Regional climate models (RCMs) are an effective approach to perform studies on land use change influences on the energy and water cycles (Gao et al., 2007). However, land use change is not typically included in RCMs due to fixed-in-time land surface data. Therefore, satellite-based images (Li et al., 2017), which can display land use change over the past 30 years, have been used to perform numerical experiments to explore the impacts on rainfall in various categories, especially for storm and heavy storm rainfall. Meanwhile, the mosaic approach, rather than the dominant approach, was employed to describe the land surface characteristics and their corresponding changes (Li et al., 2013), for which the changes in the land surface physical parameters were closer to the actual values. Therefore, land-atmosphere interactions can be more concisely represented by RCMs (Zhao and Wu, 2017a; 2018).

The impacts of land use change over East Asia include a decreased surface air temperature (SAT), with the exception of an increased SAT over southeastern China (Zhao and Wu, 2018). Rainfall has intensified in the south and weakened in the north over the East Asian summer monsoon (EASM) region (Zhao and Wu, 2017b), which could be explained by changes in the monsoonal circulation and moisture fluxes as a result of land use change. Here, land use change influences on the total rainfall (RCN) in various categories as well as on convective (RC) and non-convective (RN) rainfall, rainfall intensities, rain areas and number of rain days were further explored. Because of the great variability in spatial distribution of the rainfall, these findings could decrease the uncertainties in studies on rainfall changes using observed data due to a coarse data resolution and inhomogeneity of meteorological observation stations (Wang and Zhai, 2008) and distinguish the land use change impacts on the RC and RN, as well as their contributions to the changes in RCN. Meanwhile, RC and RN cannot be separated using observed data. However, the land use change impacts on rainfall could be interpreted by the influence of pressure gradient and temperature gradient (Zhao and Wu, 2017b). The changes in RC and RN might be quite different due to SAT changes derived from land use change, which was also an objective of this study. Strong rainfall, which might induce severe disasters, such as storm and heavy storm rainfall during the years 1991, 1998, and 2008 over the Yangtze River Delta, as well as heavy storm rainfall over Beijing on July 21, 2012, could have a considerable impact on the daily lives of the population of this area. Though disasters were not solely induced by land use change, they played a non-negligible role on the rainfall. The annual precipitation can fall mostly as strong rainfall, especially in northern China (Wang and Zhai, 2008). Therefore, an exploration of land use change impacts on strong rainfall is of great importance.

Here, land use change impacts on rainfall in various categories, especially for storm and heavy storm rainfall were explored using satellite-based images showing land use change between 1980 and 2010 (Li et al., 2017). Numerical experiments were performed using the Weather Research and Forecasting (WRF) RCM with sub-grid-scale land use characteristics and corresponding changes were considered using the mosaic approach (Li et al., 2013; Zhao and Wu, 2017b; 2018). Meanwhile, the strong rainfall impacts and contributions from changes in the RC and RN intensities (RCI and RNI, respectively), rain areas, and number of rain days were discussed in detail.

2 | EXPERIMENTAL DESIGN AND DATA

The design of the numerical experiment and data used in this study were the same as those employed in Zhao and Wu (2017b; 2018), described in detail in File S1 and Figure S1, Supporting Information, which concentrated on land use change influences on EASM-related precipitation and SAT. Accordingly, the impacts of land use change on the rainfall in various categories, especially for storm and heavy storm rainfall and contributions from changes in the RCI and RNI, rain areas, and number of rain days were discussed in this study. In general, similar model designs and physical parameter schemes were included in two numerical experiments with different land surface data from satellite images (Li et al., 2017) which was based on the Advanced Very High Resolution Radiometer (AVHRR) and Moderate Resolution Imaging Spectroradiometer (MODIS) satellite data from the long-term land use data record covering the last 30 years (Pedelty et al., 2007). The land surface data from 1980 (LU80) and 2010 (LU10) had been validated using in-situ observed land use category distributions and proven to be more concise in displaying land use distributions and land use changes, compared to the default fixed-in-time land use data (Li et al., 2017). The first experiment used fixed-in-time land surface data from 1980 (LU80), and the second experiment used fixed-in-time land surface data from 2010 (LU10). In the different land use categories, greater spatial distributions and more intense changes were observed for forests, open shrublands, grasslands, croplands, cropland/natural vegetation mosaics, and barren or sparsely vegetated areas. Although the changes and distributions were lower in urban and built-up areas, these changes were not negligible in the land use change studies. As a total, the land use change had effect on the roughness length and near-surface wind speeds, shown in Figure S2.

To concisely disclose the land use change impacts on rainfall for subregional characteristics, China was divided in eight subregions (Figure 1a), including northeast China (NE), north China (NC), east China (EC), south China (SC),...
the eastern part of northwest China (NWE), southwest China (SW), the western part of northwest China (NWW), and the Tibetan Plateau (TP). The subregions were divided according to the climate background, such as East Asian monsoon areas, including NE, NC, EC and SC, as well as SW, among which the precipitation decreased from south to north. The NWW subregion is usually considered as an arid area and is mainly controlled by the westerly flow. The NWE subregion is affected by both the EAM circulation and westerly flow. The TP subregions are the highest Plateau in the world and the complex terrain and topography tend the air to flow around the TP rather than through it (Qian, 1988), and this is influenced mainly by the India monsoon at the southern part, which is mainly controlled by the westerly currents.

3 | RESULTS

3.1 | Changes in RCN

Since the precipitation is mainly concentrated during the summer (June–July–August, JJA), the impacts of land use change on the JJA rainfall are analyzed following the marked subregional characteristics for the rainfall that could be detected (Figure 1b and Table S1) (Zhao and Wu, 2017b). Significance t tests (*, **, ***, and **** denote passing the 80, 90, 95, and 99% confidence level t tests, respectively) on changes in the summed RCN for various categories over different subregions of China expressed marked subregional characteristics. The RCN decreased in northeastern (NE, −0.068 mm/day), northern (NC, −0.10 mm/day), eastern (EC, −0.098 mm/day), and southwestern (SW, −0.022 mm/day) China as well as in the Tibetan Plateau (TP, −0.17 mm/day) of China, while the RCN was enhanced in southern China (SC, 0.31 mm/day) and the eastern (NWE, 0.10 mm/day) and western (NWW, 0.0083 mm/day) parts of northwestern China. These changes contributed to a decreased RCN over the entire country of China (CN, −0.022 mm/day) and the East Asian land areas (EAL, −0.015 mm/day). Changes in the rainfall expressed greater relative values over NE, NC, SC, and NWE and the TP, all of which are mostly located in semi-arid areas that show a greater sensitivity to land use change, except for SC.

3.2 | Changes in rainfall in various categories

According to standards from the China Meteorological Administration, the daily rainfall intensity is classified into five categories: light (0.1–10 mm/day), moderate (10–25 mm/day), heavy (25–50 mm/day), storm (50–100 mm/day), and heavy storm (greater than 100 mm/day) rain. The days with a rainfall of less than 0.1 mm/day are considered to be no rain days.

3.2.1 | Changes in RCN, rain areas, and number of rain days

The RCN changes in various categories are shown in Figure 2. In NE/EC, the RCN decreased in various categories, inducing a decrease in the cumulative RCN (Figure 1b), although the RCN of heavy storm rainfall increased. In SC/TP, the RCN in various categories increased/decreased and induced an increase/decrease in the cumulative RCN. In NC, the RCN in various categories decreased except for an increase in the RCN of light rainfall, thereby inducing a decrease in the cumulative RCN. In NWE, the RCN in various categories increased with the exception of a decreased heavy storm rainfall, inducing an increase in the cumulative RCN. Similar distributions of changes in the RCN could be detected between NWE and NWW, and there was an opposite trend for storm rain.

The changes in rain areas and number of rain days in various categories are shown in Figure 2. The rain areas in various categories consistently decreased over NC and the
However, the rain areas decreased/increased (except those for light and heavy storm rain) in NE/NWE (Figure 2). In EC, the rain areas decreased except for that of heavy storm rain. In SC, with the exception of the area of light rain, the rain areas increased. In SW, the rain areas decreased with the exception of those for light and storm rain. In NWW, the rain areas increased except for that of storm rain.

The number of rain days consisting of light rain over NE, NC, SC, and the TP and of moderate rain over SW did not change. For the other types of rain, the number of rain days generally decreased, although they increased over SC and NWE for the stronger rainfall. The number of rain days in various categories over China and EAL remained almost unchanged except for a decreased number of heavy storm rain days over China.

### 3.2.2 Relative changes in the RC, RN, and RCN in various categories

Significance $t$ tests on changes in the daily mean rainfall (RC, RN, and RCN) in various categories over the eight subregions of China, as well as all of China and the EAL under LU10-LU80 expressed nice significance, especially for the RC and RN (Figure 2). Meanwhile, the significances over subregions of China were generally larger than the ones over the entire country of China and EAL because the land-use-change induced positive and negative changes over different subregions of China canceled out.

Spatial distributions of relative changes of the precipitation, which clearly show the impacts of land use change on the RC, RN, and RCN in various categories of the subregion, are shown in Figure 3. The changed areas for the RC, RN, and RCN in various categories decreased from light to heavy storm rainfall. The changes occurred across the entire simulated domain for light rainfall, whereas the changes were mainly focused on the eastern and southern parts of the simulated domain for storm and heavy storm rainfall. Meanwhile, significance $t$ tests at 90% confidence level showed good significance and revealed the spatial distribution of land use change impacts on the precipitation. For the RCN, the changes might be small with less areas passing the
FIGURE 3  Spatial distributions of relative changes in the (a, d, g, m) RC, (b, e, h, n) RN, and (c, f, i, o) RCN in various categories [(a–c) light, (d–f) moderate, (g–i) heavy, (j–l) storm, and (m–o) heavy storm] under LU10-LU80, and the significance $t$ tests at the 90% confidence level.
significance $t$ tests, whereas the changes in RC and RN could be much greater, showing the greater impacts of land use change on the RC and RN, which induced increased (decreased) RC and decreased (increased) RN.

3.2.3 | The probability density function distributions for changed grid cells

The probability density function (PDF) distributions for the changed grid cells, which show the significance of changed grid cells due to land use change, were adopted to express whether the relative changes in grid cells were comparable in magnitude with the variability over all pixels in the subregions (i.e., subregion NE as an example at local scale and China as an example at regional scale, Figure 4, figures for other subregions were omitted).

Over NE, changed grid cells of RC for light and moderate rainfall showed remarkable single peak patterns, and the changes in RC were mostly located between −10 and 10%, whereas the values for the stronger rainfall expressed flat patterns. For light, moderate, heavy and storm rainfall, the growing grid cells for RC changes were smaller than the shrinking ones, and this was consistent with the decreased RC shown in Figure 2a (also from the weakened RCI, shown in Figure 2b). For heavy storm rainfall, the growing grid cells for RC changes were larger than the shrinking ones, whereas the changes in RC were small due to the weakened RCI. For RN, the relative changed grid cells in different categories were close, with the exception of the values for the heavy storm rainfall. For light, moderate, heavy and storm rainfall, the grid cells for RN changes decreased, whereas RN increased (Figure 2c), which could be attributed to the enhanced RNI (Figure 2d). For heavy storm rainfall, the grid cells for RN changes increased, which was consistent with the increased RN, though RNI weakly decreased. As a result, the changed grid cells of RCN were much less than that from the changes in RC and RN, due to the opposite changes between the RC and RN from the changed grid cells. For China as a whole, the changed grid cells for different changes in RC, RN and RCN were flat compared to the values over NE, showing that the relative changed grid cells over local scales (subregions of China) were weaker than those over regional scales (country-wide, China).

3.3 | Changes in storm and heavy storm rainfall

The changes in storm and heavy storm rainfall, which were greater among all categories, are shown in Figure 2. Storm rainfall increased in SC, NWE, and SW and decreased in the other subregions. Meanwhile, heavy storm rainfall increased in NE, EC, and SC, while it decreased in NC, SW, NWE, NWW, and the TP. Storm and heavy storm rainfall increased up to 10.5% (NWE) and 13.6% (NE), while it decreased up to 6.5% (TP) and 11.9% (NWE). The changes in the RC/RN/RCN (i.e., their relative changes) consisting of storm and heavy storm rain over EC and SW were small; however, their corresponding percentages among the different categories were close, with the exception of the values for heavy storm rainfall. For light, moderate, heavy and storm rainfall, the grid cells for RN changes decreased, whereas RN increased (Figure 2c), which could be attributed to the enhanced RNI (Figure 2d). For heavy storm rainfall, the grid cells for RN changes increased, which was consistent with the increased RN, though RNI weakly decreased. As a result, the changed grid cells of RCN were much less than that from the changes in RC and RN, due to the opposite changes between the RC and RN from the changed grid cells. For China as a whole, the changed grid cells for different changes in RC, RN and RCN were flat compared to the values over NE, showing that the relative changed grid cells over local scales (subregions of China) were weaker than those over regional scales (country-wide, China).

**FIGURE 4** The probability density function (PDF) distributions for changes in the grid cells of (a, d) RC, (b, e) RN, (c, f) RCN over (a–c) NE and (d–f) China overall under LU10-LU80.
categories were much larger (see Table S2). Meanwhile, changes in RCI/RNI/RCNI for storm and heavy storm rainfall due to land use change over different subregions are shown in Table S3.

Changes in the RC, RN, and RCN for storm and heavy storm rain could pass significance t tests over the eight subregions of China, with the exception of the results over NWW. Therefore, changes in the RCI/RNI/RCNI, RC/RN/RCN, as well as rain areas and number of rain days were discussed in detail over subregions of China except NWW.

3.3.1 | Storm rain

In NC, SC, and SW, changes in the RC, RN, and RCN were similar to that of RCI, RNI, and RCNI, respectively. The positive changes in the RCI/RC and RNI/RN contributed to an increase in the RCNI/RCN over SC; however, the negative (positive) change in the RCI/RC and positive (negative) changes in the RNI/RN contributed a decrease (an increase) in the RCNI/RCN over NC (SW). The negative change in the RCNI induced a decrease RCN over NC, which also resulted from the reduced rain areas (including the reduced number of rain days). Meanwhile, the positive change in the RCNI induced an increase in the RCN over SC and SW, which also resulted from the expanded rain areas, however, the number of rain days increased over SC while decreased over SW.

In NE, EC, NWE, and TP, changes in the RC, RN, and RCN were not consistently similar to that of RCI, RNI, and RCNI, respectively. The negative change in the RCI and positive change in the RNI induced an increase in the RCNI over NE while a decrease one over TP, whereas the positive change in the RCI and negative change in the RNI induced a decrease in the RCNI over EC and NWE. The negative changes in the RC and RN induced a decrease in the RCN over EC and NWE. However, the positive changes in the RC and RN induced an increase in the RCN in NE and TP, which also resulted from the reduced rain areas (including a decrease in the number of rain days). However, the inconsistency between changes in the RCNI and RCN over NE and NWE could be attributed to changes in the rain areas, for which the positive change in theRCNI induced a decrease in the RCN due to the increased rain areas (including a decrease in the number of rain days) over NE, whereas the negative change in the RCNI induced an increase in the RCN due to the expanded rain areas (including an increase in the number of rain days) over NWE.

Over all of China and the EAL, decreased/increased RCI and increased/decreased RNI each induced an increase in the RCNI. However, RC, RN, and RCN all decreased due to a decrease in the rain areas (with unchanged number of rain days).

3.3.2 | Heavy storm rain

In EC, SC, NWE, and SW, changes in the RC, RN, and RCN were similar to that of RCI, RNI, and RCNI, respectively. The positive changes in the RCI/RC and RNI/RN contributed to an increase in the RCNI/RCN over EC and SC, whereas the negative changes in the RCI/RC and RNI/RN contributed a decrease in the RCNI/RCN over NWE and SW. The positive change in the RCNI induced an increase in the RCN over EC and SC, which also resulted from the expanded rain areas (the number of rain days reduced over EC while increased over SC). However, the negative changes in the RCNI induced a decrease in the RCN over NWE and SW, which also resulted from the reduced rain areas, however, the number of rain days increased.

In NE, NC, and TP, changes in the RC, RN, and RCN were not consistently similar to that of RCI, RNI, and RCNI, respectively. The negative changes in the RCI and RNI induced a decrease in the RCNI over NE, whereas the negative change in the RCI and positive change in the RNI induced an increase in the RCNI over NC while a decrease one over TP. The positive changes in the RC and RN induced an increase in the RCN over NE, whereas the negative changes in the RCI/RC and RNI/RN contributed to a decrease in the RCNI/RCN over NC and TP. The negative changes in the RCI/RC and RNI/RN contributed to a decrease in the RCN over NE due to the expanded rain areas (including an increase in the number of rain days). However, the positive change in the RCNI induced an increase in the RCN over NE due to the reduced rain areas (including a decrease in the number of rain days). Meanwhile, the negative change in the RCNI induced a decrease in the RCN over TP, which also resulted from the reduced rain areas (including a decrease in the number of rain days).

In all of China/EAL, increases in both the RCI and RNI induced an increased RCNI. Similarly, both the RC and RN increased and induced an increase in the RCN due to increased rain areas, although the number of rain days decreased.

3.3.3 | Comparisons of time series of RCI, RNI, and RCNI between LU80 and LU10

Comparisons on time series of annual mean RCI, RNI, and RCNI between LU80 and LU10 for the storm and heavy storm rainfall over subregions of China (NE as an example) and China as a whole are shown in Figure 5, which showed the differences in time between the LU80 and LU10 time series. Though the differences for the RCNI were small over both NE and China as a whole, the values for the RCI and RNI were much greater, which could be explained by the opposite changes between the RCI and RNI due to land use change, that is, the increased (decreased) RCI and decreased (increased) RNI resulted in weakly changed RCNI. Similar results were detected over NC, EC, and SC, shown in
Furthermore, the differences for RCI, RNI, and RCNI were smaller over NE than over China as a whole, showing that the impacts of land use change on the precipitation were weaker over regional scales than those over local scales.

4 | DISCUSSION AND CONCLUSIONS

The rainfall over eastern China is closely related to the EASM, which is influenced by a low-level southwesterly jet, south Asia High, subtropical high over the northwestern Pacific, blocking high. However, the western part of northwest China is generally not influenced by the EASM and is mainly controlled by the westerly winds. The impacts of land use change on the atmospheric circulations and moisture fluxes can only be used to explain the changes in the rainfall overall, as the rainfall in different categories cannot be revealed. Changes in moisture fluxes across the entire troposphere, which were taken from Zhao and Wu (2017b) and displayed as Figure S3, are used to give simple explanations of the changes in precipitation over western China (including NWE, NWW, SWC, and TPC).

The near-surface wind speeds in JJA displayed a marked decreasing tendency (except in NE, Table S1), which could be partially explained by the increased roughness length (with the exception of a decreased one in NE, NWW, and TP) due to land use change. The weakened southwesterly, southerly, and southeasterly moisture fluxes over the EASM region caused additional moisture fluxes to persist over SC, while less was transported north and induced a decreased rainfall in NE, NC, and EC (with a decreased upward moisture flux) with increased rainfall over SC (with a decreased upward moisture flux, Zhao and Wu, 2017b). The moisture flux related to the westerly was intensified in the middle–high latitudes; however, it was generally much weaker than the EASM-related fluxes (Figure S3). Meanwhile, the intensified westerly moisture flux and increased upward moisture flux...
flux induced an increase in rainfall over NWW. The westerly moisture flux from the Arctic Ocean was generally weakened in NWE; however, the rainfall in NWE increased, which could be explained by the intensified northwesterly moisture flux over northeastern NWE and the southeasterly moisture flux along the northeastern edge of the TP, as well as the enhanced upward moisture flux (Table S1). Moisture fluxes over the TP were influenced by the dominant channel from the southern boundaries, as well as the input from the western and northern boundaries, whereas there was output at the eastern boundaries (Xie et al., 2018). The impacts of land use change showed the weakened moisture fluxes from the southern and northern boundaries, and the enhanced fluxes from the western boundaries. Though the upward moisture fluxed increased, the weakened moisture fluxes, especially from the southern part, resulted in weakened water vapor transportation and decreased precipitation over the TP areas.

The impacts of land use change on the large-scale water vapor transportation and local upward moisture fluxes, both of which play roles in the water vapor supply, were responsible for the rainfall changes over the eight subregions of China, depending on their individual contributions. Meanwhile, changes in the rainfall in various categories over the subregions of China were much greater than those for China overall and the EAL, revealing that those impacts had less influences at the regional scale compared to local scale. Furthermore, with regard to the influences on storm and heavy storm rainfall, greater changes were detected for stronger rainfall categories, suggesting the importance of including land use change in climatic change studies.

When the RC and RN were considered separately, changes in the RC and RN were consistent in different categories and contributed to greater changes in the RCN over the EC, NWE, NWW, and TP, whereas inconsistent changes contributed to smaller changes in the RCN over NE, NC, and SW, showing that the RCN changes might have been smaller; however, the RC and RN changes could have been much greater. For the results over SC, changes in the RC and RN were consistent for the storm and heavy storm rainfall, where they were inconsistent for light, moderate and heavy rainfall. The inconsistent and consistent changes between RC and RN under different subregions of China might be attributed to subregional characteristics for the impacts of land use changes on the SAT (Zhao and Wu, 2018), as well as the influenced circulation and moisture flux, especially for the impacted EASM related circulation and moisture flux (Zhao and Wu, 2017b). Changes in the RCI and RNI both displayed consistent tendencies as those of the RC and RN, respectively, with the exception of inconsistent results over EC. Meanwhile, changes in the rain areas (including the number of rain days) also played an important role in the rainfall changes among the various categories, especially for storm and heavy storm rain.

The impacts of land use change on the summed RC, RN, and RCN for various categories might be less, whereas changes in the RC, RN, and RCN for individual various categories could be much larger. Therefore, simulation results driven by satellite-derived data using the mosaic approach are beneficial for evaluating the impacts of land use change on the regional climate at different spatial scales. The new satellite-based retrieval data were efficient at reproducing land use change and decreasing the model biases (Zhao and Wu, 2017a). However, errors will inevitably exist in the land use data between the actual distribution and retrieved results. To better understand the impacts of land use change on the regional climate, investigations using land use datasets with a higher accuracy still need to be performed.

ACKNOWLEDGEMENTS

This work was supported by the National Key R&D Program of China under Grant No. 2016YFA0600403, the National Natural Science Foundation of China under Grant Nos. 41775087 and 41675149, the National Key Basic Research Program on Global Change under Grant No. 2011CB952003, and the Jiangsu Collaborative Innovation Center for Climatic Change. The authors thank the reviewers for their numerous valuable comments to improve the manuscript.

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**SUPPORTING INFORMATION**

Additional supporting information may be found online in the Supporting Information section at the end of the article.

**How to cite this article:** Zhao D, Wu J. Evaluating land use change impacts on rainfall in various categories using the Weather Research and Forecasting-mosaic approach. *Atmos Sci Lett*. 2019;20:e870. https://doi.org/10.1002/asl.870