Increasing Risk of Wild Swings between Droughts and Floods over Global Land Areas

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Abstract

Climate variability is nothing new. Of rising concern is the consecutive occurrence of reversed weather patterns — droughts followed by severe floods, which tip a precarious balance with lasting impacts on human and natural systems. Here we examined changes in the likelihood and spatial distribution of dry-to-wet precipitation events over global land surface using climate model projections. We find anthropogenic climate change is likely to stress more widespread regions with rapid see-saw changes from dry to wet spells by the end of the 21st Century, increasing the threat to water security. Additionally, Eastern North America, South and East Asia, and Eastern Africa are emerging future hotspots of extreme drought-deluge swings by yielding marked enhancements in the events' occurrence probability and spatial coverage. This study can provide useful information for policy makers to develop integrated approach to drought and flood management, while broadening the scope of research on compound climate extremes.

Keywords:
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Studies have warned us to expect more frequent and intense extreme events in the context of climate change[1,2]. With increasing frequency, many regions of the world have experienced wild weather patterns that swing from one extreme to another, dubbed as "weather whiplash" or "climate whiplash"[3,4]. While a certain amount of the swing is part of natural climate variability, what calls attention is the synchronicity of two contrasting extreme events such as droughts and floods. Floods are associated with extremes in rainfall, whereas drought is a protracted period of deficient precipitation[5]. From crippling droughts to deadly floods or vice versa, the rapid transition from one end of precipitation spectrum to the other concerns greater impacts than the sum of each individual type of event[6]. A dramatic example in this regard is the recent California. Immediately after multi-year dryness from 2012 to 2016, California, U.S. finds itself contending with the opposite: abundant precipitation and widespread flooding in the succeeding winter of 2016–2017 that damaged hundreds of roads throughout the state and hastened the failure of the Oroville Dam's primary spillway[7].

Though droughts and floods have been widely studied at regional to continental scales[8-11], it is typical to examine them individually. In the case of precipitation whiplash, droughts and floods are two sides of the same coin, spelling double trouble for agricultural yields, water quality, and human livelihood. Their successive occurrence, commingled with uneven population distribution and interconnected infrastructure systems could cause even more of a strain on nations' ability to maintain the social, economic and environmental sustainability[17-20]. However, existing studies are few and have primarily focused on specific whiplash-like events at regional scale[12-16]. A global picture is lacking, except the recent study which explored the aggregated behavior of drought-pluvial seesaws over the globe from a historical perspective[6]. As the world warms,

abrupt shifts in weather patterns — droughts followed by severe floods — are conjectured to intensify[21,22,23]. The more connected relations between opposing precipitation extremes pose a different set of questions: What is the likelihood to anticipate heavy rainfall given a preceding dry spell? Where might be exposed to alternating effects of droughts and floods more probable than before? How likely the unusual shifts in precipitation similar or greater in magnitude to those that have historically caused widespread disruption would (re)occur in the future? Without this information, it is difficult to plan ahead for the potentially increased climate volatility[17,24].

Motivated by these questions, this study delivers a probabilistic assessment of dry-to-wet precipitation events at global scale using large ensembles of the Community Earth System Model (CESM) simulations and a conditional statistical approach. At each land grid, we define droughts and floods of future projections with respect to low and high percentiles of the historical precipitation climatology. Our objective is to estimate the probability of transitioning from a significant drought year to a following extreme wet year, characterize their spatial distributions, and quantify how these attributes may be altered as a consequence of human-induced climate change by the end of the 21st Century.

A Global Pattern for Extreme Dry-to-Wet Occurrence Likelihood

As detailed in Method, we derived the probability of transitioning from extreme dry to wet states for four forty-year periods in Figure 1 and compared the results with previous studies. For instance, our framework identified a probability between 0.2~0.3 for which a dry spell is succeeded by heavy precipitation over the northern and southern part of the U.S. Great Plains in 1960–2000. Similarly, Christian et al., 2015[16] concluded that there is about 25% chance that a

significant drought year is followed by a significant pluvial year within the Great Plains using land-based precipitation data from 1896 to 2013. Our model-based findings are quantitatively consistent with the observed evidence, confirming the validity of the applied framework.

The regions of low to high probability for extreme dry-to-wet swings are shaded from light yellow to dark blue, illustrating that virtually no continent is absolutely immune to the threat of floods and droughts occurring together at the same location from a probabilistic view. Globally speaking, the likelihood of having sharp precipitation whiplash during the period of 1920–2000 approaches 0.3 (Fig. 1a and 1b). That means, if a drought had occurred in the first year, there is about 30% chance that the second year would switch to a flood risk resulting from heavy rain on average of the globe of the 20th Century. The occurrence likelihoods of dry-to-wet transition events have been on the rise since the latter half of the 20th Century and are projected to continue to rise across a wide range of latitudes in the current century (Fig. 1c and 1d). At low latitudes, it is clear that the transition probability enhances over time in the Asian monsoon regions and exceeds 0.4 over South and Southeast Asia by the mid-21st Century. The higher-than-average likelihood suggests that these areas are likely to undergo dry-to-wet shifts at a greater frequency than the majority of the world of the past century, partially due to the large increase in total rain in climatologically wet regions of the tropics associated with the increased moisture source from the warmer Indian Ocean[25]. Rainfall is also moderately increased over the extratropics of both hemispheres poleward of 50^{o} latitude in the CESM (Supplementary Figure S1-S2), consistent with projections from other Coupled Model Intercomparison Project Phase 5 models[26]. The excess rainfall can in turn contribute to raising the possibility of rapid reversals in precipitation at

high-latitude continents, e.g., Northwestern territories of Canada, Eastern Canada, Northern Europe, Western Siberia, and Eastern Russia in the result.

Another increasing trend is present at the mid-latitude continental regions including Midwest and South-Central United States and Southeastern China. As shown, the Midwest and the Four Corners of the United States — where Colorado, Utah, New Mexico and Arizona meet deepen the color after 2020s, an indication of amplified risk of flip-flop in precipitation. In concordance, USGCRP, 2018 demonstrated that communities in the Four Corners have been bouncing between desperate dryness and extreme moisture since the winter of 2017, forcing people dependent on the reliability and predictability of water to adapt[27]. While Midwest and South-Central United States are no strangers to drought-to-deluge oscillations, the concern is that more frequent vacillating weather conditions could change the storage of nutrients in the agricultural landscape and degrade the regions' quality of water supplies, pressing municipalities to seek costly remedies to provide residents with safe drinking water[28]. Enhanced likelihood is projected likewise for Arabian Gulf area, but absent for the southern Europe–Turkey region. In the midlatitudes, synoptic storms bring moist air from the ocean to the land, and sometimes they can account for more than 70% of a region's total precipitation[29]. The observed enhancement may have a link with changes in the storm tracks in a sense that pronounced storm track activity favors monthly rainfall extremes throughout the year, whereas dry spells are associated with a lack thereof[30]. Over Southern China, especially in the mid- and lower reaches of the Yangtze River valley, the elevated likelihood of drought-pluvial seesaws can be of a close relationship with the advance and retreat of the East Asian summer monsoon[31].

In the Southern Hemisphere, South America unfolds a contrasting pattern which persists from the past into the future. More explicitly, the territory is less frequently influenced by dry-wet dipole events over the northern South America and eastern Amazonia–Northeast Brazil region, while bearing a greater risk over Southwest and Southeast South America, involving Brazil, Bolivia, Paraguay, and Argentina. An analysis of precipitation climatology over the four periods reveals that precipitation is reduced over the broad Amazon and increased over the La Plata basin and central Argentina. Combining with the physical drivers that involve local soil-moisture feedbacks prevalent over the Amazon basin and remote effects of sea surface temperature over the Niño 3.4 region on the La Plata Basin, this dipolar response could be explained[32]. Additionally, we find Southern Africa and the northern Central Africa favor similar shifts in these low frequency weather patterns, potentially related to the seasonal movement of the Intertropical Convergence Zone. This finding is in line with He and Sheffield, 2020[6], although their study focuses on the interannual precipitation variability of the recent past.

Large Increase in the Global Land Areas Susceptible to Extreme Dry-to-Wet Events

To quantify changes in the risk of precipitation whiplash, we assessed the percentage of global land areas subject to different levels of dry-to-wet transition probabilities in Figure 2. According to the 1920–1960 histogram (Fig. 2a), more than half of the land is designated with a likelihood less than 30%; only about 0.4% of the land surface yields a probability greater than 50%. In other words, during two consecutive years, 0.4% of the land may expect an extreme wet spell with more than 50% chance, viz., more likely in the year subsequent to the year of extreme dryness, yet the majority of the world would get flooding rain with a less than 30% chance in the following year during the period without appreciable human-induced climate change. Land areas

associated with higher probabilities expand a little in the next 40 years. The histogram of Fig. 2b shows that the percentage of land coverage grows from 0.4% to 2.6% at a probability above 0.5, implying that 2.6% of the global land is more likely to have suffered from severe floods and droughts in consecutive years by the end of the 20th Century. Even though, locations with a likelihood higher than 0.5 are scarce, and a probability greater than 0.6 is virtually non-existent, reflecting relatively low risks of extreme flux in precipitation for the twentieth-Century world.

Looking ahead, dry-to-wet precipitation events are projected to occur at increased spatial coverage under transition probabilities above the global average (Fig. 2c and 2d), albeit the increase is slightly reduced in 2060–2100 in response to a tempered upward trend in precipitation. Approximate 9.3% and 4.3% of the spatial areas are found with transition probabilities of 0.5~0.6 and 0.6 beyond, respectively by the mid-21st Century, in contrast to 2.3% and 0.3% of the land in 1960–2000 considering the same probability levels. That is to say about 13.6% of the land might see a drought year followed by an extreme wet year at more than 50% chance, quintupling the figure in the past century. Alternatively, land areas with lower occurrence probabilities of abrupt changes in precipitation are reduced, compensating for the increase in locations having larger odds. We report there is an appreciable increase in the percentage of land areas associated with a probability exceeding the 20th Century's global average — additional 10% of the territories are likely to be depressed by the year-to-year swings from droughts to floods in the current century, despite no material difference in the annual mean precipitation over the global land regions. Such shifts can bring more frequent and intense water cycle extremes to a broader landscape, posing a new challenge to the management of already declining freshwater resources.

To identify regional contributions to the global increase, we aggregated the land points into 21 regions (Fig. 3a), largely consistent with the divisions used for examining global precipitation projections[33]. Through the bar chart analysis (Fig. 3b-e), we find the dry-to-wet precipitation events are likely to bear upon more than 70% of the Eastern North America (E.N.A) grids at the probabilities surpassing the global average, whereof more than 20% is likely to be affected at a greater-than-0.5 probability by the end of this century. The CESM projections show that it is becoming wetter in the eastern parts of North America (Supplementary Figure S1-S2), in part, because higher temperatures increase water-holding capacity and more precipitation falls as rain instead of snow[5]. With roughly 30% enlargement since the last century, the E.N.A manages to be one of the major contributors to the marked increase in land areas that are prone to whiplash of droughts and floods. Following the E.N.A are East Asia (E.As) and Eastern Africa (E.Af), subject to an analogous amount of increase with the probability beyond 0.3, and about twofold of increase when it reaches a more probable level of 0.5. Western Africa (W.Af), South Asia (S.As), Alaska (ASK) and Greenland (GLD) are projected to increase more than 20%, positioning among the top major contributors. On the contrary, a tendency towards a reduction of the drought-to-flood prone areas appears over Amazon Basin (AMZ), Central America (C.A), and Mediterranean (Med). The changes over Med could be connected to the increased anticyclonic circulation that yields increasingly stable conditions and is associated with a northward shift of the Atlantic storm track[34].

Regional Changes in the Likelihood of Extreme Dry-to-Wet Events

Figure 4 collects the dry-to-wet transition probability at each grid of the 21 land regions in a box-whisker plot to identify future hotspots of precipitation whiplash. We examined whether the difference between each of the two periods is statistically significant based on the Student *t*-test. The symbols above the boxplots notify the testing results — from one to four stars, it corresponds to significant levels of 0.05, 0.01, 0.001, and 0.0001 respectively, and ns indicates non-significant. In the first place, the box-whisker plots disclose a spatial heterogeneity with variations in the direction and magnitude of transition probabilities over space. The spatial heterogeneity may stem from different climate change impacts on micro- and macro-scale atmospheric processes controlling extreme precipitation formation in different regions, a key interpretation of studies on climate change impact on extreme precipitation in the future projections[35]. Nonetheless, we note statistically significant upward trends with dry-to-wet transition probability well beyond the global average for all the four periods over regions, including E.N.A, E.Af, S.As, North Asia (N.As) and E.As. The increasing trends in Central Asia (C.Asia), Southern South America (S.SA) and W.Af are significant for the first three 40 years while milder for the last period. With the rising trends, these regions may exhibit an increased propensity for drought-flood seesaws, consistent with our previous findings. Western North America (W.N.A) and Central North America (C.N.A)'s upward trends are less significant, owing to, in part, the large variability in spatial distributions of the extreme dry-to-wet precipitation events, whereas no clear trend is detected in the rest regions.

Excluding the climatologically dry regions such as Alaska, Greenland and North Asia, the most prominent hotspot emerging from the box-whisker plots is the E.N.A. On the one hand, a significant increase in the dry-to-wet transition probability since the 1920 vintage typifies the

E.N.A region; on the other hand, it shows the highest likelihood among the 21 regions in the current century. Other emerging hotspots include S.As, E.As, and E.Af, due to the relatively high transition probability with distinguishable increments over the study periods. Demographic growth and shifts to such whiplash-prone locations can raise the number of human beings exposed. Plus the detected increase in vulnerable land areas, a variety of natural resources could be at risks in the 21st Century, and a paradigm shift from disaster relief to prevention will be crucial for buffering the worst effects of rapid transitions between extreme precipitation and the opposite.

Research Implications

Collectively, we find the percentage of global land areas susceptible to dry-to-wet transition events has been appreciably enhanced in the 21st Century, principally due to the human-induced climate change. In addition, the anthropogenic forcings are likely to heighten the likelihood of unusual shifts in precipitation over the global land surface, while inducing disproportionate impacts at regional scales. Potential future hotspots include Eastern North America, South and East Asia, and Eastern Africa, where the increasing greenhouse emissions can yield more frequent and widespread drought-deluge fluctuations with marked enhancement in the events' occurrence probability and spatial coverage in the current century.

A warmer atmosphere is associated with a greater water-holding capacity, whose role is likely to strengthen the global hydrological cycle[36,37,38]. Enhancement in the seasonal precipitation cycle would have notable consequences such that precipitation tends to be concentrated into more intense events, with longer periods of little precipitation in between[39,40]. As a result, deluge can

206 be interspersed with very dry interludes. Local changes in the character of precipitation relevant
207 to the wild swings between droughts and floods depend upon a multitude of factors, involving
208 large-scale atmosphere circulation and topographical conditions[13,14,15,16,24,25]; other influences
209 from land–atmosphere feedback and a warming Arctic with loss of sea ice are also possible and
210 remain a subject of ongoing research[17,18]. By probing changes in the likelihood and spatial
211 distribution of dry-to-wet precipitation events, this study is expected to shed light on
212 understanding the underlying mechanisms of drought-flood cycles and provide useful
213 information for policy makers and infrastructure operators to develop integrated approach to
214 drought and flood management. It is also worth noting that the proposed approach is broadly
215 transferable and can be extended to tackle other scientific challenges related to abrupt changes in
216 climate.
217
218 While humans have long adapted to regimes of water scarcity or excess, we are vastly
219 underprepared for climate extreme events, such as the "mega" droughts, unprecedented wildfires,
220 or their combinations, also known as compound events[41,42]. According to the Intergovernmental
221 Panel on Climate Change report, compound events describe multiple climate drivers and/or
222 hazards that occur simultaneously or successively to contribute to societal or environmental
223 risk[41]. In combination, these hazards caused devastating impacts well beyond that which any one
224 of these hazards would have caused in isolation[44], and for this reason, compound events have
225 received increasing attention in the recent decade[45,46,47,48,49]. By definition, the consecutive
226 occurrence of reversed weather patterns can be considered compound events; however,
227 comparing to the concurrent climate extremes, e.g., droughts and heat waves, heavy precipitation
228 and storm surge, etc., synchronicity of contrasting extreme events has been largely overlooked.

This study aims to broaden the scope of research on compound events by calling attention to climate whiplash, in particular, the rapid see-saw changes from dry to wet spells, which may seem rare but are likely to occur more frequently with severe consequences — disrupting plant growth, jeopardizing agricultural yields, and threatening the durability and longevity of buildings, all in much quicker cycles than one would typically plan for in the near future.

Method

Project Data

The monthly precipitation data is from the National Center for Atmospheric Research's single-model 'Large Ensemble Community Project' (LENS). We obtained 37 simulations of the Community Earth System Model (CESM) at 1° × 1° spatial resolution (http://cesm.ucar.edu/projects/community-projects/LENS/) for the period of 1920-2100. The future climate is simulated assuming the representative concentration pathway 8.5, i.e., RCP8.5 scenario, in which greenhouse gas emissions continue to increase throughout the twenty-first century[50]. This is an extreme scenario, and so our results are borne with the caveat that, for lower emissions scenarios, changes might be less than presented in this study. Each ensemble member has distinct initial conditions, so that the difference between the members is due to internal variability and the ensemble mean is an estimate of the response to external forcing. Here we derived the statistics of extreme dry-to-wet events based on the CESM ensemble mean precipitation, changes of which are mainly caused by the human-induced climate change.

Defining Dry-to-Wet Events

For the purpose of this study, period from 1920 to1960 is used as the baseline to derive anomalies of precipitation which limits factors in recent changes in climate. Using these precipitation anomalies, we identify dry and wet events for four forty-year periods, including 1920-1960, 1960-2000, 2020-2060, and 2060-2100. Herein the dry-to-wet transition events are defined as the occurrence of two consecutive years during which the annual total precipitation falls under the 30^{th} percentile of the baseline climatology (in the first year) and subsequently exceeds the 70^{th} percentile of the same reference (in the following year). We have examined different thresholds, i.e., 20^{th} and 80^{th} percentiles of the baseline climatology. No material difference is observed from the current results in terms of the spatial distribution and transition probability of the dry-to-wet events, suggesting that the current finding is robust and independent of the given thresholds (Supplementary Figure S3). For both historical simulations (1920-1960 and 1960-2000) and future projections (2020-2060 and 2060-2100), we assessed the occurrence probability of dry-to-wet transition events in each model run, based on which the upper and lower uncertainty range arising from the internal variability of the CESM simulations is derived (Supplementary Figures S4).

Estimating the Probability of Dry-to-Wet Precipitation Events

Yue and Rasmussen, 2002[51] gave a thorough review about how to obtain information concerning the occurrence probabilities of one variable under different conditions. Briefly, let $f(x, y)$ be the joint probability density function (PDF) of two continuous random variables X and Y, $f_X(x)$ and $f_Y(y)$ be the marginal PDFs of X and Y, respectively, and $F_X(x)$, $F_Y(y)$, and $F(x, y)$ be the corresponding Cumulative Distribution Functions (CDFs) for their univariate and bivariate variables. The conditional PDF of X given $Y = y$ can be expressed as:

$$f_{X|Y}(x|y) = \frac{f(x,y)}{f_Y(y)} \quad (1)$$

Based on the PDF, the conditional CDF of X given $Y = y$ is derived as:

$$F_{X|Y} = \int_{-\infty}^{x} f_{X|Y}(u|y)\, du = \frac{\int_{-\infty}^{x} f(u,y)\, du}{f_Y(y)} \quad (2)$$

Similarly, the conditional CDF of $X \leq x$ given $Y \leq y$ has the following expression:

$$F'_{X|Y}(x|y) = F(x|Y \leq y) = \frac{F(x,y)}{F_Y(y)} \quad (3)$$

The exceeding probability of Equation (3) is a measure of the likelihood associated with the event $X > x$ given $Y \leq y$, which is formulated as[52]:

$$P_{X>x|Y\leq y} = 1 - F(x|Y \leq y) = 1 - \frac{F(x,y)}{F_Y(y)} \quad (4)$$

If an extremely dry event has occurred in the first year, the interest is to estimate how likely the following year would be subject to the opposite scenario of extreme wetness. Essentially, that is the probability of X conditioned upon Y, i.e., $P(X > x|Y \leq y)$, where x and y represent the thresholds for defining the wet and dry states, respectively. This conditional probability conveys the likelihood of a subsequent flood year occurring given that a prior drought year has occurred[53]. It can also be interpreted as the probability of transitioning from one state to another (herein dry to wet states) in a single step, broadly known as the one-step transition probability[54]. The key to solving Equation (4) replies on the construction of the joint distribution between X and Y. In this study, we employed the bivariate copula which allows for joining the margins and modeling the joint dependence structure between extreme wet and dry states of precipitation.

Unlike multivariate distribution functions, such as the bivariate Gaussian or Gamma distributions, copulas do not require all of the marginal distributions to come from the same

distribution[52]. Copula functions are defined as multivariate distribution functions with uniformly distributed variables on the interval [0, 1][55]:

$$F(x_1, \dots, x_i, \dots, x_n) = C\big(F(x_1), \dots, F(x_i), \dots, F(x_d)\big) = C(u_1, \dots, u_i, \dots, u_n) \quad (5)$$

where C is the CDF of the copula, and $F(x_1)$ is the marginal distribution of x_1 being uniform on the interval [0, 1], which is also denoted by u_i. Note that C connects the CDFs of the random variables (i.e., u_i), whereas $F(x_1, \dots, x_n)$ in the left-hand side represents the joint probability of the original random variables (i.e., x_i). Let $U = F(y)$ and $V = F(x)$; and u will denote a specific value of U and v will denote a specific value of V. Substituting the bivariate copula for x and y, into Equation (4), it becomes:

$$P_{X>x|Y\leq y} = 1 - C(u, v)/u \quad (6)$$

Equation (6) thus refers to the probability of transitioning from a significant dry year to a following extreme wet year, or equivalently, the occurrence likelihood of a whiplash event of drought and floods. Different copulas are available for the joint analysis of precipitation extremes. Here we examined six widely applied bivariate copulas, including Gaussian, Student t, Gumbel, Joe, Frank and Clayton at each grid of the study domain. The goodness-of-fit of copula is tested using the Akaike information criterion[56]; and the parameters of copula functions were derived using the method of maximum likelihood estimation[57].

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448

449 **Figure Legends**

450 Figure 1. The probability of dry-to-wet precipitation events for four forty-year periods including
451 1920-1960 (a), 1960-2000 (b), 2020-2060 (c) and 2060-2100 (d). The dry-to-wet transition
452 events are defined as the occurrence of two consecutive years during which the annual total
453 precipitation falls under the 30^{th} percentile of the baseline climatology (in the first year) and
454 subsequently exceeds the 70^{th} percentile of the same reference (in the following year).

455

456 Figure 2. The percentage of global land areas subject to different levels of dry-to-wet transition
457 probabilities for 1920-1960 (a), 1960-2000 (b), 2020-2060 (c) and 2060-2100 (d).

458

459 Figure 3. The percentage of global land areas subject to different levels of dry-to-wet transition
460 probabilities for 21 subregions (a) during periods of 1920-1960 (b), 1960-2000 (c), 2020-2060
461 (c) and 2060-2100 (e).

462

463 Figure 4. The probability of transitioning from a significant drought year to a following extreme
464 wet year during each of the four forty-year periods for the 21 subregions. A, B, C and D
465 correspond to the periods of 1920-1960, 1960-2000, 2020-2060 and 2060-2100, respectively.

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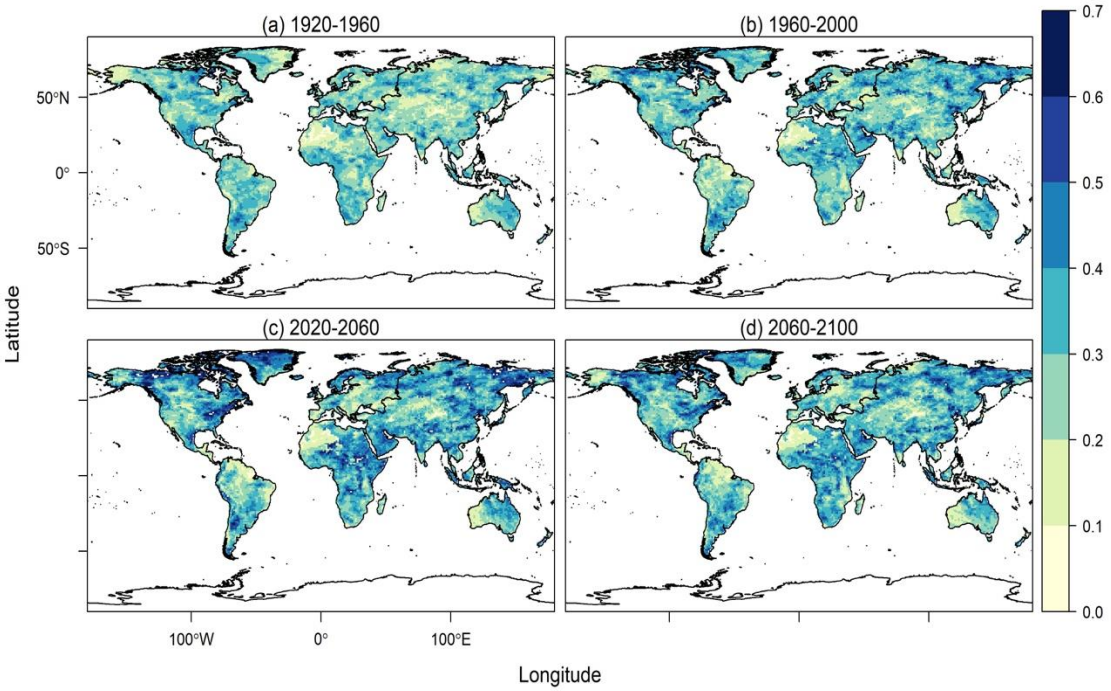


Figure 1. The probability of dry-to-wet precipitation events for four forty-year periods including 1920-1960 (a), 1960-2000 (b), 2020-2060 (c) and 2060-2100 (d). The dry-to-wet transition events are defined as the occurrence of two consecutive years during which the annual total precipitation falls under the 30th percentile of the baseline climatology (in the first year) and subsequently exceeds the 70th percentile of the same reference (in the following year).

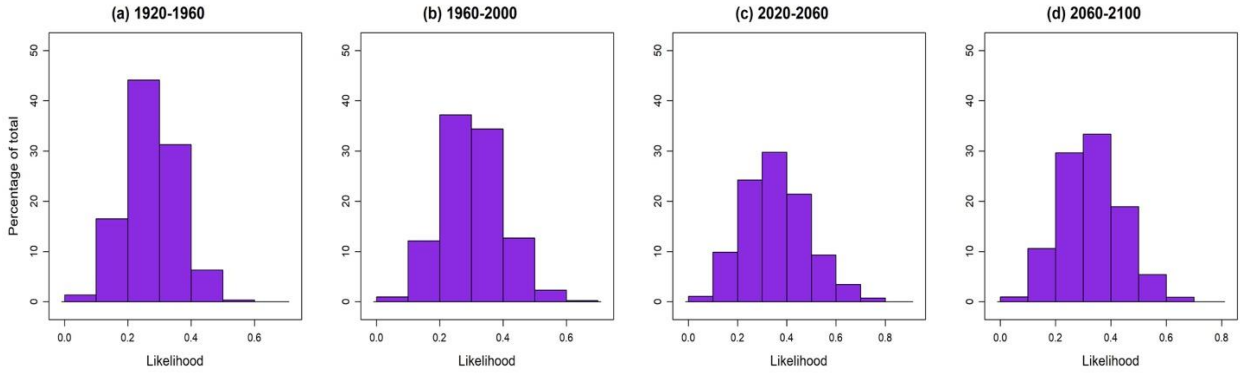


Figure 2. The percentage of global land areas subject to different levels of dry-to-wet transition probabilities for 1920-1960 (a), 1960-2000 (b), 2020-2060 (c) and 2060-2100 (d).

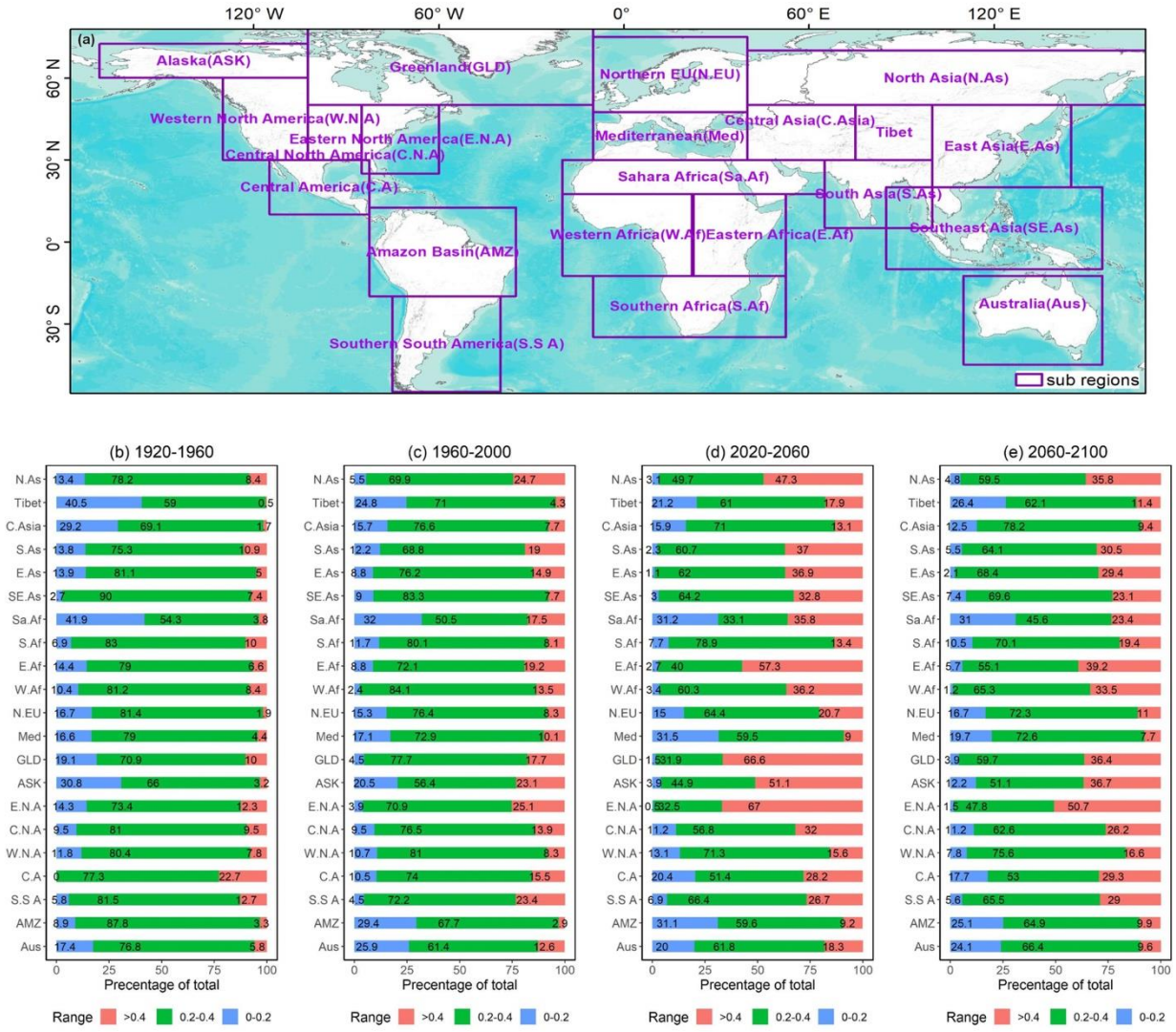
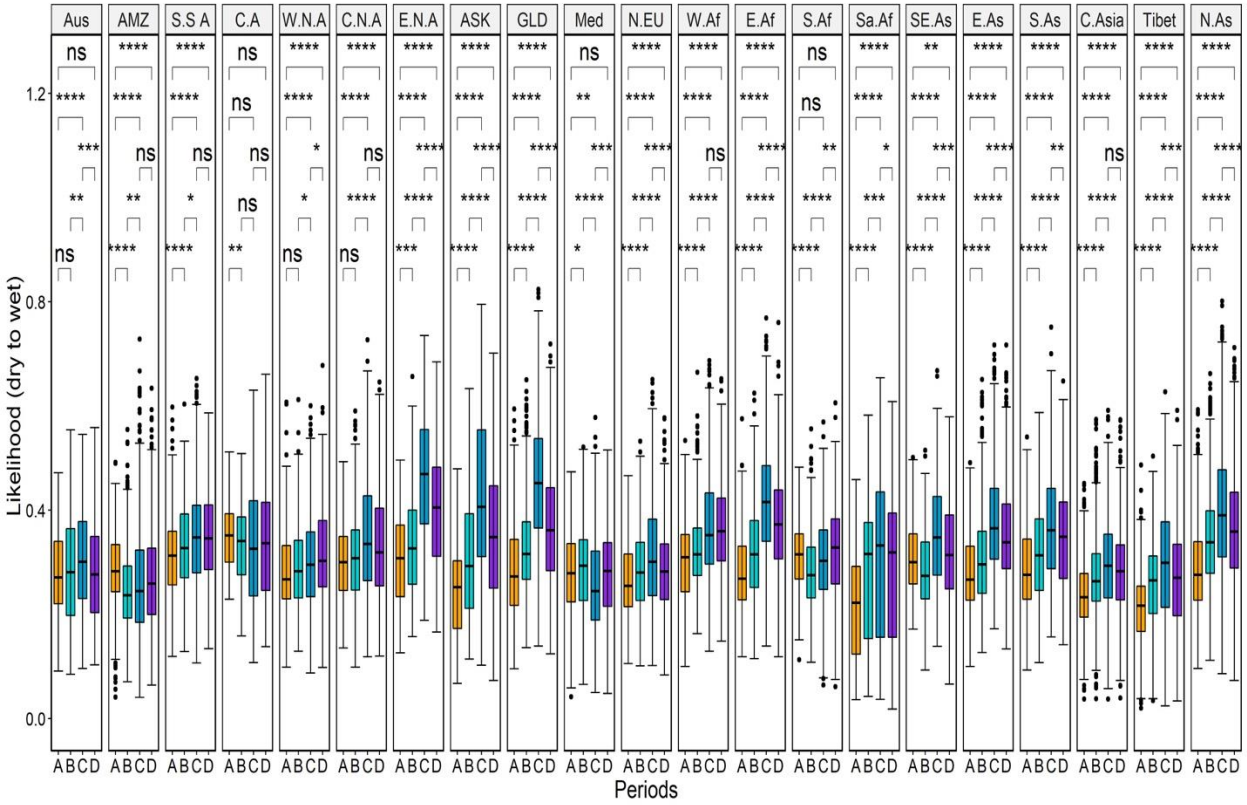


Figure 3. The percentage of global land areas subject to different levels of dry-to-wet transition probabilities for 21 subregions (a) during periods of 1920-1960 (b), 1960-2000 (c), 2020-2060 (c) and 2060-2100 (e).



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Figures

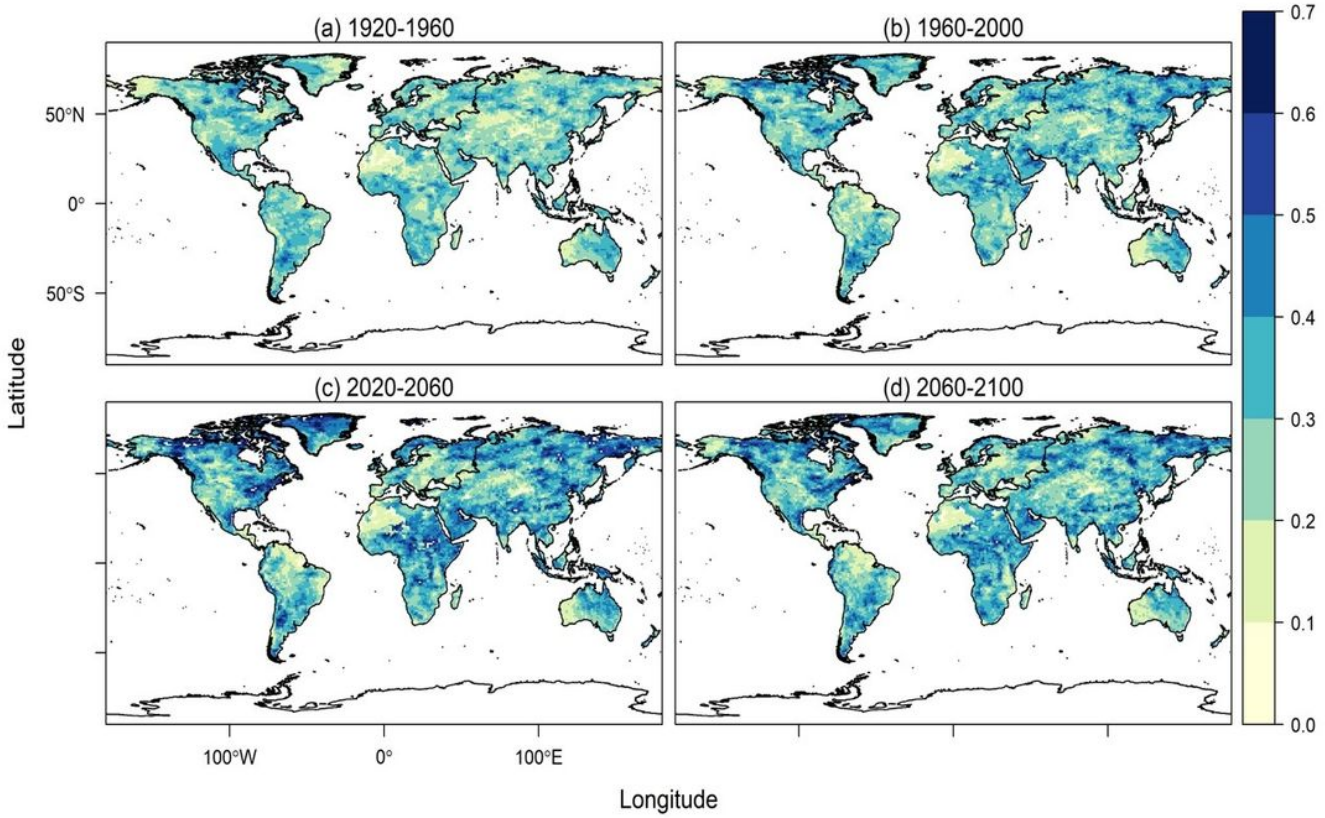

Figure 1

The probability of dry-to-wet precipitation events for four forty-year periods including 1920-1960 (a), 1960-2000 (b), 2020-2060 (c) and 2060-2100 (d). The dry-to-wet transition events are defined as the occurrence of two consecutive years during which the annual total precipitation falls under the 30th percentile of the baseline climatology (in the first year) and subsequently exceeds the 70th percentile of the same reference (in the following year). Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

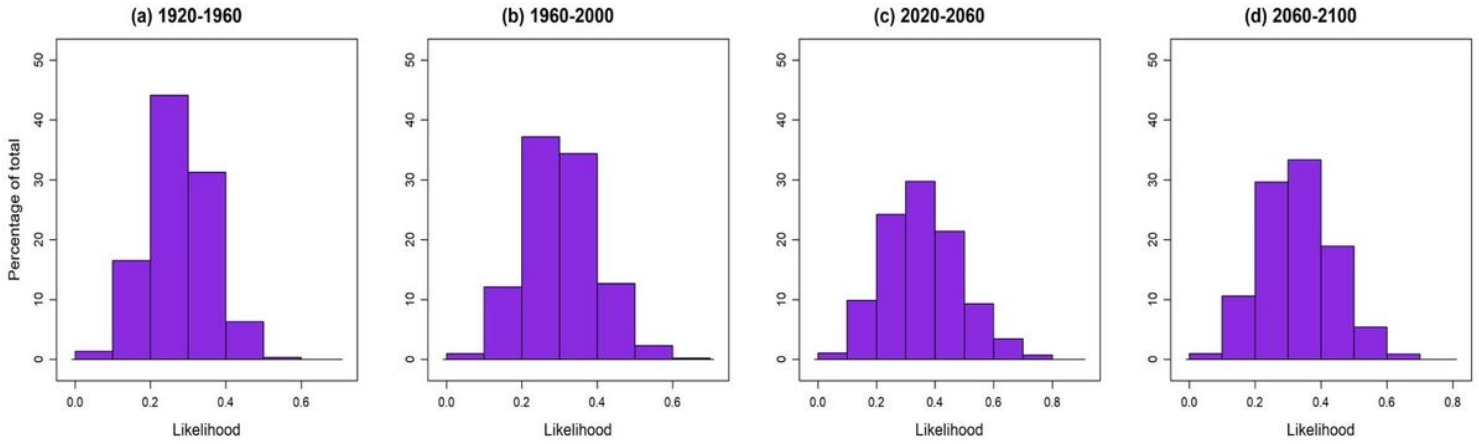

Figure 2

The percentage of global land areas subject to different levels of dry-to-wet transition probabilities for 1920-1960 (a), 1960-2000 (b), 2020-2060 (c) and 2060-2100 (d).

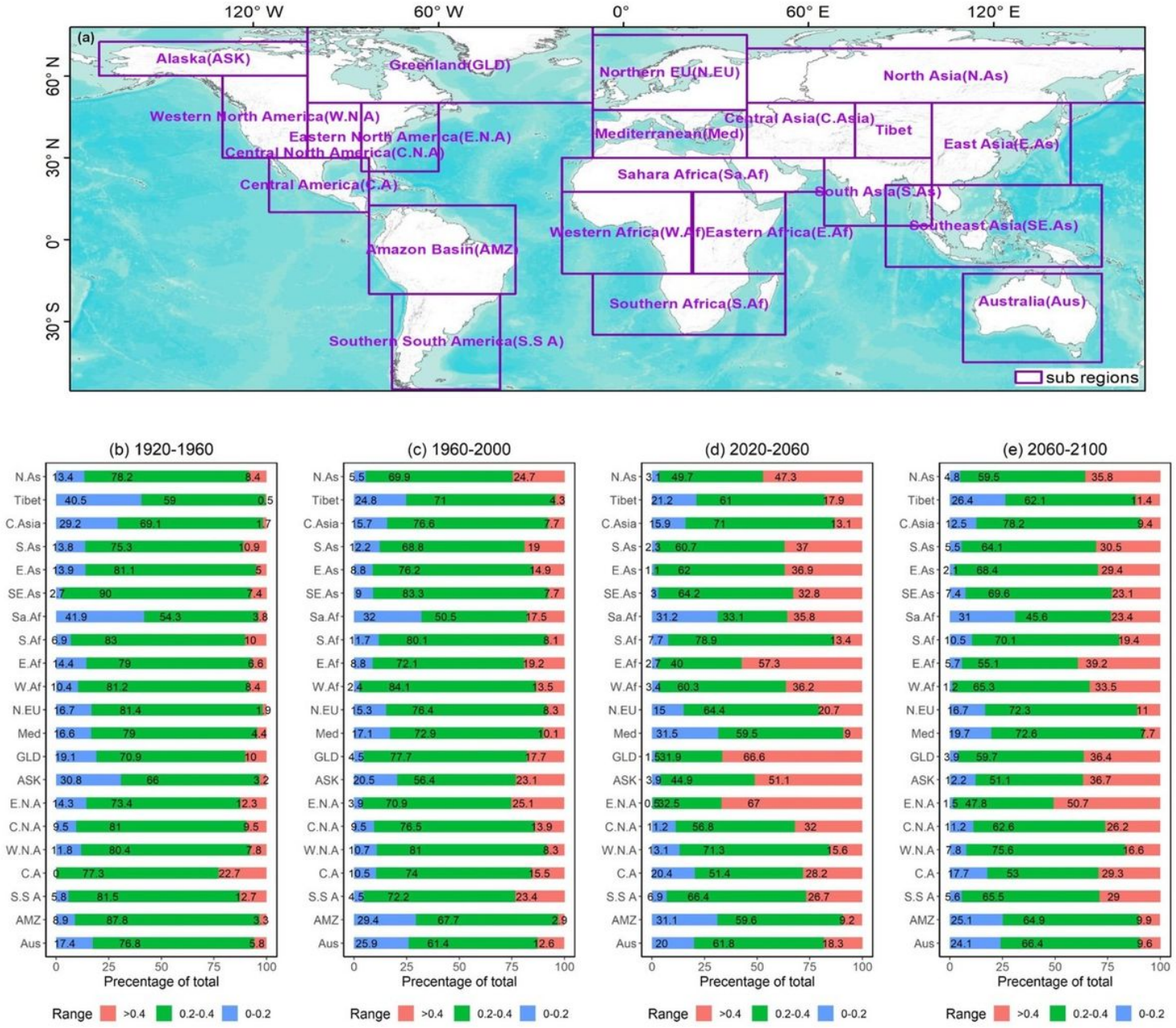

Figure 3

The percentage of global land areas subject to different levels of dry-to-wet transition probabilities for 21 subregions (a) during periods of 1920-1960 (b), 1960-2000 (c), 2020-2060 (c) and 2060-2100 (e). Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

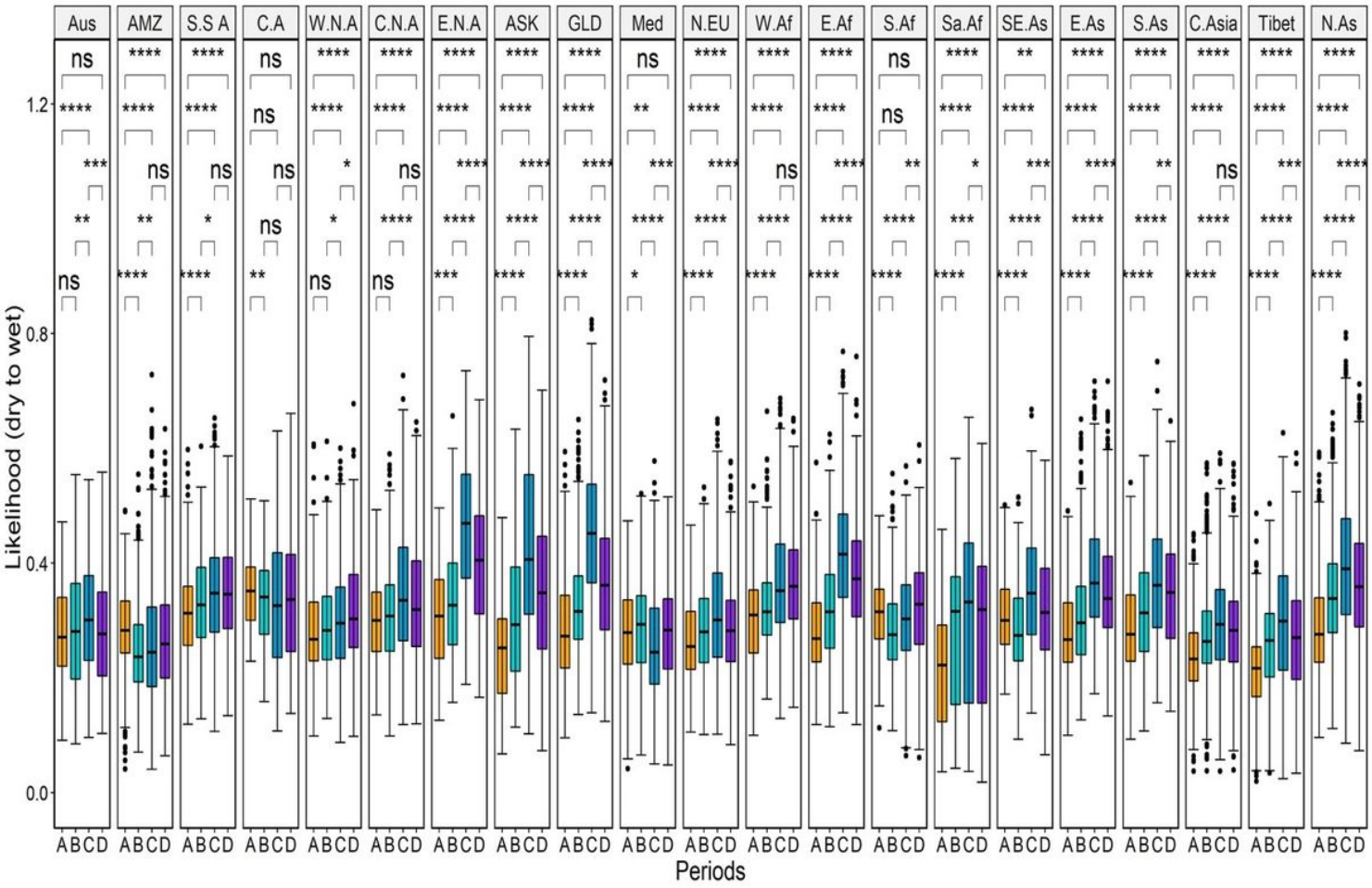

Figure 4

The probability of transitioning from a significant drought year to a following extreme wet year during each of the four forty-year periods for the 21 subregions. A, B, C and D correspond to the periods of 1920-1960, 1960-2000, 2020-2060 and 2060-2100, respectively.

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