Projected Changes in the Annual Range of Precipitation Under Stabilized 1.5°C and 2.0°C Warming Futures

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Abstract Changes in hydrological cycle under 1.5°C and 2.0°C warming are of great concern on the post-Paris Agreement agenda. In particular, the annual range of precipitation, that is, the difference between the wet and dry seasons, is important to society and ecosystem. This study examines the changes in precipitation annual range using the Community Earth System Model low-warming (CESM-LW) experiment, designed to assess climate change at stabilized 1.5°C and 2.0°C warming levels. To reflect the exact annual range in different regions, wet and dry seasons are defined for each grid point and year. Based on this metric, the precipitation annual range would increase by 3.90% (5.27%) under 1.5°C (2.0°C) warming. The additional 0.5°C of warming would increase annual range of precipitation by 1.37%. The enhancement is seen globally, except in some regions around the sub tropics. Under the additional 0.5°C of warming, a significant increase in the annual range occurs over 15% (22%) of the ocean (land) regions. The increase is associated with the enhanced precipitation during wet season. Moisture budget analysis shows that the enhancement in annual range is dominated by vertical moisture advection, which includes thermodynamic (TH, moisture) and climate dynamic (CD, circulation changes) terms. The TH term plays a dominant role, while the CD term partly offsets the effects of the TH term. The TH term dominates over most regions except for part of the tropical ocean and some of the land regions, where the CD term is also remarkable. Thus, the enhancement of the annual range of precipitation is mainly caused by the increase in moisture.

Plain Language Summary The Paris Agreement proposed a target to limit global warming to less than 2°C and pursue efforts to limit warming to less than 1.5°C. Since then, great effort has been devoted to exploring the impacts of the 1.5°C and 2.0°C warming scenarios. The changes in the seasonal cycles of precipitation have important impacts on natural and human systems but are unknown under 1.5°C and 2°C warming levels. We focus on the changes in the annual range of precipitation, which represents seasonal cycle and is defined as the difference between wet and dry seasonal rainfall in which the wet and dry seasons vary spatially and temporally. We project the changes by using CESM low-warming experiments. In the experiments, the multiyear global mean surface temperatures will stabilize at 1.5°C and 2.0°C above the preindustrial level by the end of the 21st century. We find significant increases in seasonal cycle over both ocean and land. The increase is dominated by the enhancement of precipitation during wet season. The increased seasonal cycle is caused by the increase in water vapor over most regions except for part of the tropical ocean and some of the land regions, where the effects of circulation changes are remarkable.

1. Introduction

Precipitation plays an essential role in the global hydrographic cycle (Ma & Zhou, 2015b; Trenberth, 2011). Precipitation is one of the main freshwater resources for human society, particularly in global monsoon regions (Wang et al., 2012; Zhang et al., 2018). Changes in precipitation in response to warming over the 21st century showed an increase in the contrast in precipitation between wet and dry regions and between wet and dry seasons (IPCC, 2013). The Paris Agreement in 2015 proposed a target to “hold the increase in the global average temperature to well below 2°C above preindustrial levels and pursue efforts to limit the temperature increase to 1.5°C” (UNFCCC, 2015). The climate impacts of 1.5°C warming above preindustrial levels and the additional 0.5°C of warming between the 2.0°C and 1.5°C warming targets have been of great concern to the scientific community (e.g., Frolicher et al., 2018; Li et al., 2018; Nangombe et al., 2018;...
The mechanisms of precipitation changes under global warming have been well documented. Evidence from coupled modeling shows that global precipitation tends to increase at a rate of 1–3% K⁻¹ and that precipitable water would increase at a rate of approximately 7% K⁻¹ based on Clausius-Clapeyron thermal scaling (Andrews et al., 2010; Byrne & O’Gorman, 2015; Chou & Lan, 2012; Held & Soden, 2006; Vecchi & Soden, 2007; Wentz et al., 2007). The changes in precipitation exhibit a latitudinal redistribution, with increases at high latitudes and in the deep tropics and decreases in the subtropics and some regions in the tropics (Byrne & O’Gorman, 2015; Deser et al., 2012; He & Soden, 2016; Held & Soden, 2006; Polson et al., 2013; Sanderson et al., 2017; Schef & Frierson, 2012). While tropical precipitation changes can be explained by the “wet-get-wetter” mechanism (Chou & Neelin, 2004; Chou et al., 2009) complemented by the “warmer-get-wetter” mechanism (Huang et al., 2013; Ma & Xie, 2013; Xie et al., 2010), changes in precipitation over land and monsoon regions are dominated by both thermodynamic processes associated with humidity change and dynamic processes associated with atmospheric circulation change (Byrne & O’Gorman, 2015, 2016; Chen & Zhou, 2015).

Precipitation change exhibits strong seasonal dependence (Polson et al., 2013; Seager et al., 2010; Sobel & Camargo, 2011). The annual range of precipitation would increase, which is mainly caused by the increase in water vapor in the wet season (Chou et al., 2013; Chou & Lan, 2012; Ma & Zhou, 2015b). An enhanced precipitation seasonal cycle in monsoon regions associated with global warming has also been reported (Zhang et al., 2019). It is essential to consider the changes in the seasonal cycle in the projection of precipitation changes. Nevertheless, previous studies have usually fixed the wet and dry seasons as June to August and December to February, respectively, in the Northern Hemisphere (Li et al., 2010; Wang & Ding, 2006). Neither the spatial variation (Chou et al., 2013; Ma & Zhou, 2015b) nor the temporal shifts (Chou & Lan, 2012; Ma & Zhou, 2015a; Zhang et al., 2019) in the wet and dry seasons were considered in the previous studies based on fixed seasons. Pioneering studies have demonstrated that the maximum and minimum seasons and the annual range should be defined specifically for each grid and year in global warming studies (Chou et al., 2013; Chou & Lan, 2012). The new metric considers both the spatial variation and the temporal shifts in the wet and dry seasons under global warming. Thus, this metric reflects the exact range of how precipitation changes within a year (Chou & Lan, 2012; Ma & Zhou, 2015a, 2015b).

The possible changes in the seasonal cycle were not considered in the recent projections of precipitation changes under the Paris Agreement levels of global warming (e.g., Déqué et al., 2017; Hoegh-Guldberg et al., 2018; Jacob et al., 2018; Kjellstrom et al., 2018; Sanderson et al., 2016, 2017; Vautard et al., 2014). In this study, we aim to estimate the precipitation change in 1.5°C and 2.0°C warming futures by considering the changes in the seasonal cycle. We hope to answer the following questions: (1) How would the annual range of precipitation change under the 1.5°C and 2.0°C warming levels, and what are the associated mechanisms? (2) What are the expected differences between the 1.5°C and 2.0°C warming climates?

The remainder of the paper is organized as follows. In section 2, we describe the data used in this study and define the annual range of precipitation. We examine changes in the global averages and spatial distribution of the annual range of precipitation under 1.5°C and an additional 0.5°C of warming (i.e., 2.0°C of warming total) in section 3. A summary and discussion are presented in section 4.

2. Data and Analysis Methods

2.1. Data Description

In our analysis, the outputs of historical climate simulations, the 1.5°C and 2.0°C warming scenario projections from the NCAR (National Center for Atmospheric Research) CESM (Community Earth System Model version 1.1.1; Kay et al., 2015), are used. The model data are available at a resolution of 1° and have 11 ensemble members in each experiment. The CESM-LW experiments provide a unique resource for assessing climate change under the 1.5°C and 2°C warming targets as it is specifically designed to achieve these stabilized warming scenarios, for the first time in coupled simulations (Sanderson et al., 2017). The CESM model
has high performances in simulating precipitation in the current climate among CMIP5 models (e.g., Gettelman et al., 2019; Knutti et al., 2013; Sanderson et al., 2015).

The historical simulations cover the period from 1920 to 2005. The projections cover the period from 2006 to 2100. In the 1.5°C and 2.0°C warming experiments, the multiyear global mean surface temperatures will stabilize at 1.5°C and 2.0°C above preindustrial levels in approximately 2050 and 2070, respectively (termed as 1.5degNE and 2.0degNE). To obtain the 1.5°C and 2.0°C scenarios, a simple Minimal Complexity Earth Simulator (MiCES, 2016) was first used to produce a set of greenhouse gas (GHG) emission pathways that were applied to the CESM for the period from 2006 to 2100 (Sanderson et al., 2017). In the projection, the GHG pathway followed Representative Concentration Pathway 8.5 (RCP8.5) until 2017 and was then changed for the 1.5°C and 2.0°C warming experiments. Except for GHG forcing, all other anthropogenic forcings (e.g., aerosol emissions, land use, and ozone) followed the RCP8.5 scenario (Riahi et al., 2011; Taylor et al., 2012). For more details about the experimental design, please refer to Sanderson et al. (2017).

In addition, the observed monthly precipitation from the Global Precipitation Climatology Project version 2.3 (GPCP v2.3) was used to validate the model. The GPCP v2.3 data set is based on satellite and rain gauge data with a spatial resolution of 2.5° × 2.5° (Adler et al., 2003).

### 2.2. Analysis Method

In our analysis, the seasonal average is the average of three continuous months using 3-month running averages. At each grid, the maximum (wet) season is defined as the three continuous months when the average precipitation reaches its maximum in each year. The corresponding climate variables (e.g., evaporation, wind vector, and specific humidity) in the maximum season are also extracted. The above definition and data processing are also applied to the minimum (dry) season based on the minimum seasonal average precipitation.

The annual range of precipitation, which represents the intensity of seasonal cycle, is defined as the difference between the maximum and minimum seasonal precipitation in each year and at each grid, following the design of previous studies (Chou et al., 2013; Chou & Lan, 2012; Ma & Zhou, 2015b). The definition of annual range provides an exact range of how the precipitation range changes and considers the spatial variation and temporal transition of the wet and dry seasons under global warming (Chou & Lan, 2012; Ma & Zhou, 2015a, 2015b). In comparison, the traditional fixed-month wet and dry seasons are defined as June to August (JJA) and December to February (DJF) in the Northern Hemisphere, respectively, and vice versa in the Southern Hemisphere.

Following Sanderson et al. (2017), we take a 30-year time slice from 1976 to 2005 as the reference climate and one from 2071 to 2100 as the warming climate. The changes in the maximum and minimum seasons and the annual range are defined as the difference between the reference and warming climate. The effect under 0.5°C (0.5deg) extra warming is defined as the difference between 1.5degNE and 2.0degNE from 2071 to 2100.

The seasonal changes in precipitation on a single grid might be nonsignificant. To measure the area fraction with significant changes, we calculate the spatial probability density function (PDF) in precipitation changes. The local precipitation changes are first normalized by the local mean in the base climate and then weighted according to their grid area. The weighted changes at each grid point fall in the corresponding bin of the PDF derived from the nonparametric assessment of the PDF. The spatial PDF was proposed by Fischer et al. (2013) and used for the detection of extreme climate events (e.g., Fischer & Knutti, 2014; Zhao et al., 2020; Zhao & Zhou, 2019).

To understand the mechanisms for the changes in the annual range of precipitation, a moisture budget was diagnosed as in previous studies (Chou et al., 2013; Chou & Lan, 2012; Held & Soden, 2006; Seager et al., 2010). The moisture budget equation is as follows:

\[
P' = -\delta_i \langle q' \rangle - \langle \nabla \cdot V_q \rangle + E' + \delta,
\]

where \( P \) is the precipitation, \( E \) is the evaporation, \( q \) is the specific humidity, \( V \) represents the wind vector, and \( \delta \) is a residual term (Res). The symbol \( \langle \cdot \rangle \) represents a mass integration: \( \langle X \rangle = \frac{1}{\mathcal{E}} \int_{P_s}^{P_T} X dp \), where \( P_s \) and \( P_T \) are the surface (1,000 hPa) and top (100 hPa) of the troposphere, respectively. The \( \langle \cdot \rangle' \) represents the...
seasonally averaged changes in the warming climate relative to the reference climate. When discussing the effect of the 0.5 deg-extra warming, the reference climate is the mean state for the period from 2071 to 2100 in the 1.5 degNE warming scenario. $-\partial_t \langle q \rangle$ in Equation 1 is the time partial derivative of $q$, which can be ignored since its seasonal mean value is much smaller than the other terms (e.g., Li et al., 2017; Ma & Zhou, 2015b). According to the mass conservation equation, the convergence of moisture flux $-\langle \nabla \cdot V q \rangle'$ can be divided into two terms: vertical moisture advection $-\langle \omega \partial_p q \rangle'$ and horizontal moisture advection $-\langle V_h \cdot \nabla_h q \rangle'$ (Chou et al., 2009; Chou & Lan, 2012; Ma & Zhou, 2015b). Therefore, Equation 1 can be reformulated as follows:

$$P' \approx -\langle \omega \partial_p q \rangle' - \langle V_h \cdot \nabla_h q \rangle' + E' + \delta,$$

where $\omega$ is the vertical pressure velocity and $V_h$ is the horizontal wind vector.

Following previous studies (e.g., Chou et al., 2013; Chou & Lan, 2012), the changes in vertical moisture advection $-\langle \omega \partial_p q \rangle'$ can be further divided as follows:

$$-\langle \omega \partial_p q \rangle' = -\langle \omega \partial_p q \rangle' - \langle \omega \partial_p q \rangle - \langle \omega \partial_p q \rangle.$$

where $\langle \cdot \rangle$ in Equation 3 denotes the mean state in the reference climate. $-\langle \omega \partial_p q \rangle'$ is dominated by changes in water vapor, which are mainly caused by temperature changes and are usually called the...
thermodynamic component (TH), while \( -\langle \omega \partial_p q \rangle \) is associated with changes in circulation and is called the climate dynamic component (CD; Chou et al., 2009; Held & Soden, 2006). The last term in Equation 3 is the nonlinear term, which is generally smaller than \( -\langle \omega \partial_p q \rangle \) and \( -\langle \omega \partial_p q \rangle \) (Chou et al., 2013; Chou & Lan, 2012; Li et al., 2017; Ma & Zhou, 2015b); thus, this term is neglected in this study.

In our analysis, we focus on the multimember ensemble mean and the changes between 70°S and 70°N. The results are first calculated for each ensemble member, and then all members are averaged to obtain the ensemble mean. On the global scale, the significant changes need to exceed twice the standard deviation (STD) of the ensemble-annual precipitation in a warming climate, while regionally, the significant changes need to exceed one STD (Sanderson et al., 2017). In addition, the significance tests for quantitative results are performed using a t test. The levels of significance (\( \alpha \)) are given after the quantitative results.

3. Results

3.1. Mean States of Precipitation in the Maximum and Minimum Seasons

To evaluate the performance of the model, we present the present-day mean precipitation over 1979–2005 derived from the GPCP and CESM (Figure 1). The pattern correlation coefficient (PCC) and the root-mean-square difference (RMSD) between the simulation and the observation are calculated. The observed precipitation in the maximum season ranges from 0.50–15.00 mm day\(^{-1}\) with centers in the tropics (Figure 1a). Less precipitation is seen in the subtropical desert and at high latitudes. The precipitation in the minimum season has a weak amplitude of 0–4.00 mm day\(^{-1}\) except around the Intertropical Convergence Zone (ITCZ), South Pacific Convergence Zone (SPCZ), and Amazon. The spatial pattern of the annual range is similar to that of precipitation in the maximum season. Notable annual ranges occur at low latitudes and in monsoon regions except around the equatorial ocean (stippling in Figure 1c).

The simulation reasonably reproduces the observed spatial patterns of climatological precipitation, with PCC (RMSD) values of 0.86 (2.47 mm day\(^{-1}\)), 0.85 (0.82 mm day\(^{-1}\)), and 0.84 (2.48 mm day\(^{-1}\)) in the maximum and minimum seasons and the annual range, respectively (Figures 1d–1f). A notable bias exists over the tropical region, which is known as the “double-ITCZ” bias. The magnitude of precipitation in the maximum season and the annual range over the tropical South Atlantic, tropical western Pacific, and Indian Ocean are overestimated, while the precipitation in the maximum season over Europe and Amazon is underestimated. In addition, the variabilities of precipitation are underestimated compared to that in GPCP (Figure 2, black lines).

The above assessment indicates that the simulated precipitation in the maximum (wet), minimum (dry) seasons, and the annual range are generally consistent with the observations.

3.2. Changes in the Annual Range of Precipitation Under Stabilized Warming

3.2.1. Global Mean Change

To understand the global changes under the two warming scenarios, we present the global-average time series of precipitation anomalies (Figure 2). The precipitation increases will stabilize after the 2060s. The annual range of precipitation increases significantly by 3.90% (0.16 mm day\(^{-1}\), \( \alpha < 0.01 \)) and 5.27%
(0.21 mm day$^{-1}$, $\alpha < 0.01$) in the 1.5degNE and 2.0degNE scenarios, respectively, relative to that in the reference climate. These increases are due to the increases in precipitation in the maximum season (Figure 2a and Table 1), while the changes in precipitation in the minimum season are relatively small (Figure 2b). In addition, the enhancements in the annual range are larger than those in the annual mean (3.3% and 4.5%, respectively, from Sanderson et al. (2017)).

Associated with the 0.5deg-extra warming scenario, the annual range increases significantly by 1.37% (0.06 mm day$^{-1}$, $\alpha < 0.01$), which is caused by the significant increase in precipitation of 0.98% (0.05 mm day$^{-1}$, $\alpha < 0.01$) in the maximum season (Table 1). The increase is larger than the annual mean (1.2% from Sanderson et al. (2017)). Thus, 0.5°C of extra warming will further enhance the seasonal cycle of precipitation.

### 3.2.2. Spatial Distribution

To investigate the regional response to warming, we present the spatial pattern of the precipitation changes (Figure 3). The annual range of precipitation shows significant increases in most areas under the 1.5degNE scenario except for some regions in the subtropics (Figure 3c). The pattern of the annual range is similar to

**Table 1**

| Changes in Precipitation in the Maximum and Minimum Seasons and the Annual Range in 2071–2100 Relative to 1976–2005 in Each Season Under the 1.5degNE and 2.0degNE Warming Scenarios and That Associated With 0.5deg-Extra Warming |
|-----------------------------------------------|
| Max. precip (%) | Min. precip (%) | Annual range (%) |
| 1.5degNE | 3.53 (3.40–3.59)$^a$ | 2.45 (2.24–2.90)$^a$ | 3.90 (3.59–4.28)$^a$ |
| 2.0degNE | 4.51 (4.34–4.67)$^a$ | 2.29 (2.06–2.46)$^a$ | 5.27 (5.01–5.56)$^a$ |
| 0.5deg | 0.98 (0.73–1.20)$^a$ | −0.16 (−0.51–0.14) | 1.37 (0.92–1.69)$^a$ |

*Note.* The uncertainty is the 25th to 75th expected range among the ensemble members.

*The multimember ensemble mean is significant at the 1% level and exceeds twice the standard deviation (STD) of the ensemble-annual precipitation in a warming climate.

**Figure 3.** Changes between the 1.5degNE warming climate in 2071–2100 and the reference climate in 1976–2005 (a–c) and the difference between 2.0degNE and 1.5degNE in 2071–2100 (d–f) in the maximum (a, d) and the minimum (b, e) seasons and the annual range (c, f), where the significant regions are stippled. Significance is defined as a pixel in which the multimember ensemble mean exceeds the standard deviation of the 2071–2100 values in the 1.5degNE (left) and 2.0degNE (right) ensemble-annual mean precipitation. The units are mm day$^{-1}$. 

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that seen for the maximum season (Figure 3a), implying that the enhancement of the annual range is due to the increases in precipitation in the maximum season. The changes in precipitation in the minimum season are not significant, except for the significant increases over the Southern Ocean, North Pacific, and part of eastern North America (Figure 3b). The spatial pattern of the precipitation differences between the 1.5degNE and 2.0degNE warming scenarios is similar to that in the 1.5degNE scenario, except in the tropical northern Atlantic (Figures 3d–3f).

Under the 0.5deg-extra warming scenario, significant increases occur over land regions, including southeastern South America, South China, north of the Indo-China Peninsula, and parts of Africa. A previous study indicated that regionally significant differences in annual mean precipitation between the 1.5degNE and 2.0degNE warming scenarios occurred only over the ocean (Sanderson et al., 2017). The paradox was reduced by the nonsignificant changes in precipitation in the minimum season and due to the neglect of the seasonal cycle in previous studies. Thus, significant increases in the annual range occurred over both land and ocean areas under the 0.5deg-extra warming scenario, and such increases resulted in a significant enhancement in the seasonal cycle of precipitation.
To measure the spatial extent of the increasing annual range, the changes in precipitation are aggregated spatially, and we present the fraction of areas experiencing certain changes (Figure 4). A total of 21.63–24.49% ($\alpha < 0.01$) and 38.86–43.03% ($\alpha < 0.01$) of ocean and land areas, respectively, would experience a significant enhancement in the annual range. In comparison, small ocean and land fractions are seen in the fixed-month season (dashed lines in Figures 4c and 4f). Notably, the coverage with enhancement is lower in the fixed wet season (Figures 4a and 4d) and higher in the fixed dry season (Figures 4b and 4e).

The PDFs of precipitation changes under the 0.5deg-extra warming scenario are shown in Figure 5. Approximately 15.22% ($\alpha < 0.01$) and 22.00% ($\alpha < 0.01$) of the ocean and land fractions would see a significant enlargement in the annual range, respectively (Figures 5c and 5f). The enlargements are induced by the enhancement of precipitation in the maximum season (Figures 5a and 5d). In addition, the land fraction with an enhanced seasonal cycle is larger than that over the ocean.

The results above indicate that the annual range of precipitation will significantly increase over 26.45–29.78% ($\alpha < 0.01$) of the global area under the two low-warming scenarios. Associated with 0.5deg-extra warming, over 15.22% ($\alpha < 0.01$) of the global ocean and 22.00% ($\alpha < 0.01$) of the global land area will experience a significant enhancement in the annual range, which is mainly due to the increase in precipitation in the maximum season.

3.3. Moisture Budget and Mechanisms
3.3.1. Global Mean Moisture Budget
To understand the mechanism inducing the global enhancement of the annual range, we evaluate the global mean moisture budget. In the 1.5degNE scenario, evaporation ($E$) and vertical moisture advection ($-\langle \omega \hat{\rho} q \rangle$)
are the dominant terms in the maximum and minimum seasons (Figures 6a and 6b). The increase in the precipitation annual range (0.16 mm day\(^{-1}\), \(\alpha < 0.01\)) is dominated by \(- \langle \omega \cdot \partial q \rangle (0.16 \text{ mm day}^{-1}, \alpha < 0.01)\) (Figure 6c). Since evaporation makes comparable positive contributions in the maximum and minimum seasons, it contributes little to the increases in the annual range in terms of the global mean.

In addition, to reveal the relative effects of water vapor and circulation changes, we further decompose the \(- \langle \omega \cdot \partial q \rangle\) into the TH term (thermodynamic term, \(- \langle \omega \cdot \partial q \rangle\)) and the CD term (climate dynamic term, \(- \langle \omega \cdot \partial q \rangle\)). The TH term (0.21 mm day\(^{-1}\), \(\alpha < 0.01\)) is the dominant term in \(- \langle \omega \cdot \partial q \rangle\), while the CD term (0.06 mm day\(^{-1}\), \(\alpha < 0.01\)) partly offsets the effects of the TH term. Therefore, the enhancement of the annual range is mainly induced by the increase in water vapor in the 1.5degNE warming scenario.

Associated with 0.5°C of extra warming, the enhancement of the annual range of precipitation (0.06 mm day\(^{-1}\), \(\alpha < 0.01\)) is also dominated by the vertical moisture advection (0.07 mm day\(^{-1}\), \(\alpha < 0.01\)) associated with the TH term (0.10 mm day\(^{-1}\), \(\alpha < 0.01\)). The CD term (−0.03 mm day\(^{-1}\), \(\alpha < 0.01\)) partly offsets the TH term, and the contribution from other terms to the precipitation annual range can be ignored. Therefore, in both the 1.5degNE and the 0.5deg-extra warming scenarios, the increases in water vapor dominate the global mean enhancement of the annual range of precipitation.

### 3.3.2. Spatial Distribution

We further examine the spatial patterns of the dominant terms. At middle to high latitudes (30°–70°N and 30°–70°S), evaporation contributes to the significant increase in precipitation in the maximum season, except in part of the North Atlantic (Figure 7a). In the minimum season, significant anomalies are seen only over the ocean at the middle to high latitudes and the northwestern Eurasian continent (Figure 7b). At regional
scales, evaporation contributes significantly to the increased annual range at middle to high latitudes (Figure 7c).

The positive anomalies of vertical moisture advection dominate the increase in the annual range over the tropics and parts of the midlatitudes, while the negative anomalies of vertical moisture advection cause the decrease in the annual range over the subtropical South Indian Ocean and part of the subtropical North Pacific (Figure 7f). In the maximum season, the positive anomalies of vertical moisture advection significantly enhance the precipitation in the tropics except over the subtropical ocean (Figure 7d), while the vertical moisture advection makes a negative contribution to the precipitation in the minimum season with reverse vertical motion over most part of North America and the Atlantic, part of Africa and South America, western and central Asia, and tropical and subtropical Pacific except the western Pacific (Figure 7e). Due to the opposite anomalies in the two seasons, $-\langle \omega \frac{\partial }{\partial z} q \rangle$ makes a significant positive contribution to the annual range of precipitation, except over part of the subtropical ocean.

To quantify the relative effects of water vapor and vertical motion anomalies, we calculate the changes in the TH and CD terms (Figure 8). In the warming climate, the TH term significantly enhances the annual range except in part of the east coast of the tropical Atlantic and Pacific (Figure 8c). In the maximum season, the TH term increases almost globally except in subsidence regions over the east coast of the ocean and cold tongue (Figure 8a). The change in the TH term exhibits a “wet-get-wetter” pattern (cf. Figures 8a–8c to

Figure 7. Changes in evaporation (a–c) and $-\langle \omega \frac{\partial }{\partial z} q \rangle$ (d–f) between the 1.5degNE warming scenario from 2071 to 2100 and the reference climate in the maximum (a, d) and minimum (b, e) seasons and the annual range (c, f), where significant regions are stippled. Significance is defined as a pixel in which the multimember ensemble exceeds the standard deviation of the 2071–2100 values in the 1.5degNE ensemble-annual mean precipitation. The units are mm day$^{-1}$.
Figures 1a–1c). The TH term decreases in the minimum season when rainfall is rare in the mean state. The patterns of the CD term are opposite to those of the TH term except in the equatorial Pacific in the annual range (Figures 8d–8f). The magnitude of the CD term is weaker than that of the TH term almost globally except over the equatorial Pacific (Figures 8d and 8f). Over the equatorial Pacific, the increase in the annual range is dominated by the CD term. Therefore, in the 1.5degNE warming scenario, the increase in moisture dominates the enhancement of the annual range except over the equatorial Pacific.

To reveal the mechanism that causes significant changes associated with 0.5deg extra warming, we show the spatial difference between the 1.5degNE and 2.0degNE scenarios in the moisture budget (Figure 9). A significant decrease in evaporation is seen over the northwestern Eurasian continent, part of northern North America, and the North Atlantic, while a significant increase is seen over part of the northern North Pacific (Figures 9a and 9c). The significant increase in the annual range is dominated by the vertical moisture advection term. This result is due to the enhancement of the TH term over the low latitudes, except in the eastern Pacific and Atlantic away from the equator, tropical South America, and part of the tropical Indian Ocean, where the decrease is due to the CD term (Figures 9d and 9f and Figures 10a, 10c, 10d, and 10f). The patterns of the TH term follow the patterns of climatological precipitation (Figures 10a–10c). In addition, over the equatorial Pacific, the increase in vertical moisture advection is due to the CD term (Figures 10d and 10f).
In addition, the annual range of precipitation exhibits a significant difference between the 1.5degNE and 2.0degNE scenarios over land regions (Figure 3f), which is caused by vertical moisture advection in all areas except northern North America (Figure 9f). The increase in the TH term causes a significant increase in the annual range of precipitation over southeastern South America, South China, the northern Indo-China Peninsula, and Africa (Figure 10c). The significant increase in the precipitation annual range over the Indo-China Peninsula and South China is due to the CD term, while the significant decrease in the annual range over northwestern South America is due to the CD term (Figure 10f).

The results above suggest that the enhancement of precipitation in the annual range is dominated by the increases in water vapor (TH) in the tropics, except in the equatorial Pacific, where the vertical motion (CD) enhances the annual range of precipitation. Over the South Indian Ocean and subtropical central and eastern Pacific, the decrease in annual range is dominated by the decrease in vertical motion (CD). At middle to high latitudes, the increase in the annual range is mainly caused by the evaporation and the TH term. Associated with 0.5deg-extra warming, land regions experience significant enhancements in the annual range, and the increase in the TH term plays a dominant role in all areas except East Asia and South America, where the contribution of the CD term is remarkable. This result suggests that over these land regions, the seasonal cycle is enhanced, although the increase in annual mean precipitation is not significant.
4. Conclusion

In response to global warming, the annual range of precipitation, namely, the difference between the precipitation in the maximum and minimum seasons, would change and exert substantial impacts on water management. Focusing on the Paris Agreement global warming targets, we investigated the changes in the annual range of precipitation under the 1.5degNE and 2.0degNE warming scenarios, as well as the underlying mechanisms, using CESM low-warming experiments. The major conclusions are summarized below:

1. The annual range of precipitation would experience a significant increase of 3.90% ($\alpha < 0.01$ and same below) and 5.27% globally in the 1.5degNE and 2.0degNE warming scenarios, respectively. This increase is mainly caused by the enhancement in the maximum season, while precipitation in the minimum season changes only slightly. Regionally, 21.63% (24.49%) of ocean and 38.86% (43.03%) of land area would experience a significant enhancement of the annual range under 1.5°C (2.0°C) warming. Nevertheless, the subtropics would see a decreased annual range due to the larger decreases in precipitation in the maximum season than in the minimum season.

2. Associated with 0.5deg-extra warming, the annual range of precipitation would experience a significant increase of 1.37% globally. Over 22.00% (15.22%) of land (ocean) regions, the annual range will increase significantly.
3. According to the moisture budget analysis, the enhancement of the annual range of precipitation is dominated by vertical moisture advection, of which the TH term (due to atmospheric moistening) dominates (0.21 mm day\(^{-1}\) [5.15%] and 0.31 mm day\(^{-1}\) [7.60%]), while the CD term (due to circulation changes) partly offsets the TH term (−0.06 mm day\(^{-1}\) [−1.41%] and −0.09 mm day\(^{-1}\) [−2.14%] globally under 1.5°C and 2.0°C warming, respectively). The mechanism also holds for the 0.5deg-extra warming. While the TH term dominates the enhancements of the precipitation annual range for the global mean and most of the regions, the CD term can be more important over other regions, including the equatorial Pacific and part of the subtropical oceans.

Despite the insignificant changes in the annual mean precipitation globally and over most land regions with the 0.5°C additional warming, the precipitation annual range would change robustly at global and regional scales. This result suggests profound impacts on water management, agriculture, and ecosystems, which are sensitive to precipitation changes in wet and dry seasons (Dore, 2005; Zhang et al., 2012). The projected enhancement of the annual range indicates that the contrast between the wet and dry seasons would become stronger, resulting in a more uneven distribution of freshwater resources within a year. The probability of flooding would increase in the wet season in the two low-warming scenarios and further enhance in association with 0.5°C of extra warming.

The wet and dry seasons are defined at each grid point and for each year in this study, which considers the shifts in the rainy season between regions and those caused by global warming. Consequently, the precipitation annual range, as well as its changes estimated here, is larger than that based on fixed wet/dry seasons in previous studies (e.g., Sanderson et al., 2017; Wang & Ding, 2006).

**Data Availability Statement**

The GPCP V2.3 data set was acquired from https://www.esrl.noaa.gov/psd/data/gridded/data.gpcp.html. The NCAR CESM low-warming experiment products were acquired from https://www.earthsystemgrid.org/dataset/ucar.cgd.ccsm4.lowwarming.html?df = true.

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