Both dynamic and thermodynamic components contribute to precipitation increase but dynamic change is more important at high warming level.

Abstract
Understanding the link between future changes in East Asian summer monsoon (EASM) and global warming levels is of great importance for regional climate change adaptation and mitigation in East Asia. Here, we analyze the projected changes in EASM circulation and precipitation under different warming levels from 1.5 to 5 °C above the preindustrial global mean temperature, using large-ensemble simulations conducted with Canadian Earth System Model version 2. We find that the model projects enhanced monsoon circulation and precipitation with global warming. The 850-hPa meridional winds, precipitation, and 500-hPa vertical ascending motion will be enhanced nonlinearly, while the total column precipitable water will increase quasi-linearly. The increase in precipitable water in the wet EASM region is only slightly greater than global average but the increase in precipitation is much greater than global one, with enhanced 500-hPa vertical ascending motion contrary to global mean. The increased low-level land-sea thermal contrast leads to the enhanced EASM meridional circulation and thus bring a large amount of moisture into Eastern China, providing favorable conditions for additional increase in precipitation. A simplified moisture budget analysis shows that the dynamic component related to strengthening monsoon circulation plays dominant role in the increase in EASM precipitation when the global temperature increases by more than approximately 2 °C, while the thermodynamic component caused by increased water vapor is what is important when the warming is smaller.

Plain Language Summary
Changes in East Asian summer monsoon (EASM) circulation and precipitation have great impacts on human society, agriculture and energy in East Asia. Previous studies rarely investigated EASM circulation and precipitation changes under specific global mean temperature increases, such as 1.5 to 5 °C of warming. Here, we focus on EASM circulation and precipitation changes linked with different global warming levels. Four EASM metrics (850-hPa meridional wind, precipitation, precipitable water, and 500-hPa vertical velocity) are examined to reflect EASM system changes based on Canadian Earth System Model version 2 large-ensemble runs. We find that EASM low-level meridional wind, precipitation, and midlevel vertical ascending motion will be enhanced nonlinearly with warming, while precipitable water will increase quasi-linearly with warming. The increase in EASM precipitation is greater than global average, accompanied by increasing vertical ascending motion and strengthened southerly winds. When global mean near-surface air temperature increases by more than 2 °C, the dynamic component plays dominant role in the increased EASM precipitation, while the thermodynamic factor plays a secondary role. These results provide useful information for developing strategies for climate change policy in East Asia.

1. Introduction
East Asian summer monsoon (EASM) is an important part of the global monsoon system. It has complex temporal and spatial characteristics and exerts major impacts on the Asian climate (Kang et al., 2002; Sperber et al., 2013; Sun & Ding, 2009; Wang et al., 2008; Wang & Li, 2004). East Asia is located within the largest continent (Eurasia), with the largest ocean (Pacific) to the east and the Qinghai-Tibet Plateau.
to the west. The significant land-sea thermal contrast and complex topography drive EASM circulation and affect the precipitation pattern in this region. In recent decades, EASM circulation has significantly weakened (Ding et al., 2008, 2009; Wang et al., 2013). The summer precipitation pattern in eastern China shifted from a pattern with southern drought and northern flooding to the opposite pattern with southern flooding and northern drought (Ding et al., 2008, 2009), exerting serious impacts on agriculture and other important economic sectors.

With rapid development of climate models, the models performance has been greatly improved and are able to reproduce basic climatological features and observed changes in the global monsoon system (Christensen et al., 2013). For the EASM, the current generation of models can reproduce its general distribution features, although there are still some errors in simulating precipitation amount along the Meiyu-Baiu-Changma rain belt and the northward extension of monsoons in China and Japan (Chen & Sun, 2013; Sperber et al., 2013; Zhou et al., 2018). The development of climate models provides a solid basis for projection of future monsoon changes under different global warming scenarios. Some studies have shown that global monsoon precipitation will increase significantly in the 21st century with continued increases in anthropogenic greenhouse gases (Hsu et al., 2012; Hsu et al., 2013; Kim et al., 2008; Lee & Wang, 2014). Lee and Wang (2014) pointed out that the Asian terrestrial monsoon region will extend westward and that the monsoon asymmetry of the north-south and east-west hemispheres will increase. The Intergovernmental Panel on Climate Change Fifth Assessment Report concluded that “Taken together with identified model agreement on future changes, the global monsoon, aggregated over all monsoon systems, is likely to strengthen in the 21st century with increases in its area and intensity, while the monsoon circulation weakens” (Christensen et al., 2013).

Although most global summer monsoons show enhanced precipitation and weakened circulation with increased greenhouse gases, the EASM shows a unique feature with both increased precipitation and increased circulation. Sun and Ding (2009) used Coupled Model Intercomparison Project phase 3 (CMIP3) models under the Special Report on Emissions Scenarios A1B scenario and found that both EASM precipitation and circulation will increase significantly after the 2040s. In the lower troposphere, the change in circulation is projected to be related to the enhancement of subtropical anticyclones in the northwestern Pacific, while in the upper troposphere, it is related to the northeasterly airflow on the eastern side of anomalous anticyclones over South Asia. Chen and Sun (2013) focused on the precipitation change in the EASM region with CMIP phase 5 (CMIP5) models. They found that the precipitation amount and intensity will increase and frequency will decrease over eastern China and around Japan. The model ensemble mean was very similar to the six-best-model ensemble mean. Using 15 coupled CMIP5 models, Wang et al. (2018) showed the main mode of EASM precipitation changing from tripolar to dipolar under global warming of 1.5 °C and significant enhancement of lower-troposphere monsoon circulation. Liu et al. (2018) used the CMIP5 models to project future EASM precipitation changes under 1.5 and 2 °C of warming based on the emergent constraint method. They found that the anomalous shift of the East Asian subtropical jet and the northwestern Pacific subtropical high may be the drivers of the intermodel difference in future EASM projections. By adjusting these errors, they project the increased EASM precipitation is due to a significant increase in water vapor. The effect of downward movement caused by the change in the subtropical jet in East Asia is weaker than the effect of the increase in water vapor in the Meiyu-Baiu-Changma rain belt.

Focusing on the precipitation change, some studies used the moisture budget method to estimate the contributions of the dynamic and thermodynamic components to precipitation changes. Hsu et al. (2012) pointed out that the enhanced monsoon precipitation is mainly due to enhanced water vapor convergence and surface evaporation, based on three high-resolution atmospheric circulation models from sea surface temperature forcing experiments. Qu et al. (2014) found that water vapor and evaporation associated with global warming are the two major contributors to the increase in EASM precipitation based on 16 CMIP5 models. Zhou et al. (2017) showed that the EASM circulation change is the most uncertain source in the model by comparing three sets of precipitation equations. It is possible to correct for the influence of the thermodynamic process on EASM precipitation changes by using the observation constraint method.

All of these previous studies show that under future warming scenarios, the EASM precipitation will increase while the EASM circulation changes will differ slightly from those predicted by various studies based on different EASM indices. These studies are generally based on multimodel ensembles and...
describe EASM changes with evolving time under emission scenarios but not with global mean temperature increases or targets. Although a few studies have investigated EASM changes under 1.5 or 2 °C of warming in recent years, there is still a lack of studies on the link between the EASM changes and global warming levels, such as warming of 1.5 to 5 °C. It would also be interesting to investigate contributions of dynamic and thermodynamic factors to EASM precipitation changes. These issues will be the focus of this paper. The remainder of the paper is organized as follows: The data and methods are described in section 2. Section 3 evaluates the performance of Canadian Earth System Model version 2 (CanESM2) in simulating EASM circulation and precipitation. We analyze future changes in the EASM system under different global warming levels in section 4. In section 5, a simple water vapor budget method is used to quantify the relative contributions of thermodynamic and dynamic factors to the EASM precipitation changes. The conclusion is given in section 6.

2. Data and Methods

2.1. Observational and Model Data

The observational data used in this study include (1) monthly precipitation data at a 2.5° × 2.5° longitude by latitude resolution from the Global Precipitation Climatology Project (GPCP, 1979–2016; Adler et al., 2003) and the Center for Climate Prediction Merged Analysis of Precipitation (CMAP, 1979–2016; Xie & Arkin, 1997) and (2) monthly zonal winds, meridional winds, specific humidity, and vertical velocity (omega) for 1,000–100 hPa from European Centre for Medium-Range Weather Forecasts Reanalysis (ERA)–Interim (1979–2016; Dee et al., 2011) and the National Center for Environmental Prediction (NCEP1, 1979–2016; Kalnay et al., 1996). The horizontal resolution of the data from ERA–Interim was 1.5° × 1.5°, while that from the NCEP1 was 2.5° × 2.5°. All the data were converted to T63 resolution (approximately 2.81° resolution) to ensure that they were comparable with CanESM2 model outputs.

The model data used here are from large-ensemble runs of CanESM2 (Arora et al., 2011). This large ensemble includes 50 simulations that are driven by historical anthropogenic and natural external forcing for 1950–2005 and the RCP8.5 scenario for 2006–2100 for different initial conditions (Fyfe et al., 2017). The coupled model, CanESM2, includes an atmospheric model (CanAM4, Von Salzen et al., 2013), an ocean model (CanOM4), a terrestrial carbon model (CTEM), and an ocean carbon model (CMOC, Arora & Boer, 2010). The outputs of the CanESM2 runs were subjected to T63 triangular truncation. To obtain the global mean near-surface air temperature (GMST) changes relative to the preindustrial period, the results from CanESM2 that were part of the CMIP5 were also used. The historical runs with a five-member ensemble were used to estimate the GMST for 1850–2005.

2.2. EASM Indices and Key Study Region

There have been different views on the definition of EASM intensity. Early studies widely used a sea level pressure-based index defined by Guo (1983) as the EASM index. This index is based on the sea level pressure difference between 110°E and 160°E in the range of 10–50°N and thus has a clear physical implication for the relationship between EASM intensity and land-sea thermal contrast. However, Zhou et al. (2009) pointed out that climate models generally show poor performance in simulating past variation in zonal land-sea thermal contrasts because of the lack of important physical processes and incorrect parameterization of subgrid-scale processes in climate models. Wang et al. (2008) compared 25 EASM indices from different studies and showed that different indices reflected different aspects of the EASM. Some indices correlated well with precipitation changes in the Yangtze River Valley, while some monsoon indices well reflected precipitation variation in northern China. Based on the traditional understanding of EASM intensity, a strong EASM should be related to a strong northward advance of the EASM circulation system and above-normal precipitation in northern China (Ding et al., 2008; Guo, 1992), and vice versa. Here we simply use the 850-hPa meridional wind and precipitation averaged in the region of 22.5–40°N, 105–120°E (box in Figure 1) to directly reflect the intensity of the EASM system, which includes both circulation and precipitation. The former variable reflects the northward advance of the EASM, while the latter represents the total precipitation amount in that region. This EASM circulation index is significantly correlated with precipitation in northern part of the region. We also find that the conclusion about future EASM changes can change slightly depending on the definition of the monsoon indices.
2.3. Global Warming Levels

We use two baseline periods to estimate future changes in EASM circulation and precipitation and their relationships with different global warming levels of 1.5 to 5 °C. The first baseline period is the preindustrial period of 1850–1900. Following the international climate change negotiation agreement, this period is used as the baseline for the calculation of GMST changes or global warming levels of 1.5 to 5 °C relative to the preindustrial period in CanESM2. The second baseline period is the current climate, which is used to estimate future changes in EASM circulation and precipitation such that the estimates can be compared with current conditions. Because of the high climate sensitivity of CanESM2, the warming levels are adjusted based on observed warming. We define the 1 °C warming period in 1995–2004 in CanESM2 as the current climate since the observed GMST in 2017–2018 was approximately 1 °C above the preindustrial level. As such, the GMST increased by 1.0, 1.5, 2, 3, 4, and 5 °C compared with the preindustrial level in the models corresponding to the following six 10-year periods in CanESM2: 1995–2004 (0.983 °C), 2007–2016 (1.454 °C), 2021–2030 (1.981 °C), 2042–2051 (2.958 °C), 2061–2070 (3.978 °C), and 2079–2088 (4.980 °C). For the GMST changes, these warming levels from 1 to 5 °C correspond to the GMST increase roughly by 0.5, 1, 2, 3, and 4 °C relative to the current climate. We also test the influence of different baseline periods on our results. We use the scatter plots based on different combination with three baseline periods in Figures 4, 5, 8, and 10: (a) using the current climate (1995–2004) as the baseline period for all the monsoon metrics and using the preindustrial period (1850–1900) as the baseline period for the GMST (red lines); (b) using the 1995–2004 as the baseline period for all the monsoon metrics and GMST (black lines); and (c) using the preindustrial period (1850–1900) as the baseline period for all the monsoon metrics and GMST (blue lines, only for EASM 850 hPa meridional wind and precipitation). Our tests show that the use of different baseline periods leads to similar conclusions for future EASM changes. For other figures in the analyses hereafter, unless otherwise stated, the GMST changes are relative to the preindustrial period, and the EASM changes are relative to the current climate (1 °C of warming).

2.4. Land-Sea Thermal Contrasts

The large-scale monsoon system is mainly driven by the land-sea thermal contrast. In East Asia, the thermal contrast between the Asian continent and its surrounding oceans exerts a major influence on EASM changes (Dai et al., 2013; Kamae et al., 2014; Sun & Ding, 2011). Dai et al. (2013) defined land-sea thermal contrast indices using the area-averaged thickness in the upper (200–500 hPa) and lower (500–850 hPa) troposphere.
in Asian monsoon regions and found a clear relationship between the EASM and these thermal contrasts. Following their definition, the west-east (TEupper; TElower) gradient of the geopotential height difference in the upper and lower troposphere in the EASM region is defined as follows:

\[
TE_{\text{upper}} = Z(200–500 \text{ hPa}; 100–115^\circ E, 22.5–40^\circ N)
\]

\[
- Z(200–500 \text{ hPa}; 135^\circ–150^\circ E, 22.5–40^\circ N)
\]

\[
TE_{\text{lower}} = Z(500–850 \text{ hPa}; 100^\circ–115^\circ E, 22.5–40^\circ N)
\]

\[
- Z(500–850 \text{ hPa}; 135^\circ–150^\circ E, 22.5–40^\circ N)
\]

These indices are used for the definition of land-sea thermal contrasts in the EASM region and to discuss their dynamic relationships with EASM circulation.

2.5. Contributions of Dynamic and Thermodynamic Components to Precipitation Changes

Precipitation changes under global warming can be separated into contributions from thermodynamic and dynamic components (Chou et al., 2009; Held & Soden, 2006; Kusunoki & Arakawa, 2012; Seager & Vecchi, 2010; Sooraj et al., 2015; Zhou et al., 2017). Using the moisture budget decomposition method, different authors proposed complete and simplified formulas with which to estimate the rainfall changes contributed by changes in atmospheric specific humidity (thermodynamic component) and circulation (dynamic component). The strengths of the simplified formula are that it is simple and efficient, and the results are comparable to those from the complete formula. The intermodel uncertainty of rainfall changes can be well explained with this formula in the tropics (Huang et al., 2013) and the EASM region (Zhou et al., 2017). Here, we use the simplified moisture budget decomposition method proposed by Huang et al. (2013) to decompose the precipitation in the EASM region into

\[
\Delta P \sim - \frac{1}{\rho g} (\bar{q} \Delta \omega + \Delta q \cdot \omega)
\]

where \( q \) denotes surface specific humidity, \( \omega \) is the pressure velocity at 500 hPa, and lateral advection has been neglected. The overbar and \( \Delta \) denote the values for the current climate (1995–2004) and the changes in these values in the future climate relative to the current climate, respectively. The two terms on the right-hand side of the equation represent the dynamic (warmer-gets-wetter effect) and thermodynamic (wet-gets-wetter effect) components, respectively.

The simplified water vapor budget method can generally be used to analyze the dynamic and thermodynamic processes of precipitation changes for tropical oceans and regions with precipitation exceeding 4 mm/day (Huang et al., 2013; Huang & Xie, 2015; Zhou et al., 2017). The area-averaged daily precipitation in the EASM area is approximately 4–5 mm/day; therefore, this method should be applicable. However, one should be cautious and acknowledge that this simplified budget cannot completely distinguish the contributions of thermodynamic and dynamic processes because of the possible interaction between moisture and vertical motion changes.

3. Verification of Model Performance in Simulating EASM Circulation and Precipitation

The model-simulated 30-year (1977–2006) means of 850-hPa meridional wind, precipitation, 1,000- to 300-hPa vertically integrated specific humidity, and 500-hPa vertical velocity are compared with the observations (1986–2015) during the period when the GMST increased by the same amount (approximately 0.69 °C) above the preindustrial level (Figure 1). CanESM2 well reproduces the observed summer (June-July-August, JJA) means of 850-hPa meridional wind and precipitation based on different observational data sets. The southwesterly airflows from the Indian Ocean to the South China Sea all the way to eastern China can be well captured by the model ensemble mean. The cross-equatorial flow and the large-scale anticyclone in the northwestern Pacific are also well simulated. The quantitative analyses (Table 1) show that the model-simulated summer 850-hPa meridional wind, precipitation, 1,000- to 300-hPa vertically integrated specific humidity, 500-hPa vertical velocity, and their first and second annual cycles all show strong correlations with the observations, with all the correlation coefficients in the box region (20°S to 70°N, 40–180°E).
Table 1
Pearson Correlation Coefficients (PCCs) (20°S to 70°N, 40–180°E) Between Model Ensemble Means (1977–2006) and Observed Values (1986–2015) of June-July-August (JJA) 850-hPa Meridional Wind, Precipitation, 1,000- to 300-hPa Integral Specific Humidity, and 500-hPa Vertical Velocity and Two Annual Cycles

| PCC       | ERA-Interim/GPCP | NCEP/CMAP |
|-----------|------------------|-----------|
| V-850 hPa | 0.90             | 0.93      |
| Precipitation | 0.78            | 0.83      |
| Q 1,000-300 hPa | 0.94           | 0.84      |
| Omega-500 hPa | 0.72            | 0.70      |
| First annual cycle | 0.79          | 0.81      |
| Second annual cycle | 0.85          | 0.86      |

Note. The first annual cycle is defined as summer (JJA) minus winter (December-January-February; DJF) precipitation, and the second annual cycle is defined as spring (March-April-May; MAM) minus autumn (September-October-November; SON) precipitation. The observed 850-hPa meridional wind, 1,000- to 300-hPa integral specific humidity, and 500-hPa vertical velocity are based on ERA-Interim and NCEP data. Precipitation and its two annual cycles are based on GPCP and CMAP data.

Table 2
The Standard Deviation (STD) of June-July-August (JJA) 850-hPa Meridional Wind (m/s), Precipitation (mm/day), 1,000- to 300-hPa Integral Specific Humidity (g/kg), and 500-hPa Omega Velocity (Pa/s) in the EASM Region From CanESM2 (1977–2006) and Observations (1986–2015)

| STD       | Model       | ERA-Interim/GPCP | NCEP/CMAP |
|-----------|-------------|------------------|-----------|
| V-850 hPa | 0.59 (0.44–0.71) | 0.52             | 0.49      |
| Precipitation | 0.51 (0.41–0.61) | 0.51            | 0.44      |
| Q 1,000-300 hPa | 0.25 (0.17–0.32) | 0.21            | 0.19      |
| Omega-500 hPa | 0.0059 (0.003–0.008) | 0.0069         | 0.0057    |

Note. The STD of the model is the median value from 50 runs, and the brackets denote the 5–95% range of the 50-run spread.

being greater than 0.7, which indicates the good performance of the model in reproducing the basic climatological features of the EASM.

Table 2 shows the comparison between the observed and model-simulated standard deviations (STDs) of the four EASM metrics. First, the STDs of all the EASM metrics are calculated for the 50 simulations from the historical experiments, and then the median values and their 5–95% ranges are estimated. The model generally reproduces the observed variability for 850-hPa meridional wind, precipitation, precipitable water, and 500-hPa vertical velocity. The observed STDs are all located in the 50-run range of the model, indicating the good capability of the model to reproduce the variability of the observational data.

4. Future Changes in the EASM Under Different Global Warming Levels

4.1. Spatial Distribution

Figure 2 shows the spatial distributions of changes in EASM circulation and precipitation (left column), as well as in precipitable water and 500-hPa vertical velocity (right column), under different global warming levels. As the GMST increases from 1.5 to 5 °C, the low-level southwesterly airflows in eastern China come from the strengthened low-level cyclonic airflows around the Asian continent and the Tibetan Plateau as well as strengthened anticyclonic airflows over the Northwestern Pacific. The former can be related to more rapid warming over the Asian continent than in the ocean (IPCC, 2013; Zhou et al., 2018), while the latter may be related to the warming over the Pacific and the shift of the Walker circulation (Lee & Wang, 2014; Zhou et al., 2018). The strengthened southwesterly monsoonal airflows bring a large amount of moisture into East Asia (Figure 3). With the increased moisture content and enhanced vertical ascending motion (Figure 3) in eastern China, the precipitation will increase steadily in the future. It is also clear that the low-level southwesterly airflows from the Indian Ocean to the Pacific will all be strengthened, indicating strengthening of low-level monsoon airflow around the region.

4.2. Relationship Between EASM Changes and Global Warming Levels

Figure 4 shows scatter plots between the four EASM metrics and the GMST changes. The results are quite similar based on different baseline periods. There is a quasi-linear relationship between the changes in precipitable water and the increase in GMST, while the changes in 850-hPa meridional wind, precipitation, and 500-hPa vertical ascending motion show a nonlinear increase with GMST warming. Table 3 clearly shows these relationships with the GMST changes relative to the preindustrial period and the EASM changes relative to the current climate. The precipitable water increases by 7.8%/K, 8.5%/K, and 8.1%/K with 1 to 2 °C, 2 to 3 °C, and 4 to 5 °C of warming, respectively, which is slightly higher than global average and the estimate of ~7%/K based on the Clapryon-Clausius equation (Held & Soden, 2006). The changes in EASM precipitation are 3.5%/K, 6.0%/K, 6.1%/K, and 5.0%/K, respectively, for each additional degree increase, which is a nonlinear increase and much greater than global average. Additionally, the changes in 850-hPa meridional wind and 500-hPa vertical velocity show a nonlinear increase for each additional degree increase, indicating nonlinear changes in these variables with the GMST increase. Compared with the global average, precipitation increase in the EASM region is much greater and vertical motion shows opposite change compared with that at global scale. This pattern reveals that the wet EASM region will become wetter due to enhanced monsoon circulation and precipitation, which is different from the projections for the global monsoon regions. The Intergovernmental Panel on Climate Change Fifth Assessment Report has concluded that most other monsoon regions
will experience weakened circulation and enhanced precipitation with global warming (IPCC, 2013). To understand the dynamic reasons behind the increased monsoon circulation, the link between the changes in GMST and land-sea thermal contrast are investigated. In East Asia, during the period 1979–
Figure 3. Same as Figure 2, but for 1,000- to 100-hPa integral water vapor transport (left column, kg/m/s/hPa) and vertical motion (right column, m/s for meridional velocity and Pa/s for vertical velocity; the vertical velocity is multiplied by 100). Vectors denote changes that are significant at the 0.05 level.
in 2016, the reanalysis data (NCEP1 and European Centre for Medium-Range Weather Forecasts) show that the low-level land–sea thermal contrast TE_lower is significantly correlated with the 850-hPa meridional wind index (the correlation coefficient is 0.52), while the upper-level thermal contrasts TE_upper do not show a significant correlation. Figure 5 shows that with the GMST increase, the low-level thermal contrasts TE_lower will increase almost linearly and the TE_upper will almost not change. The linear increase of TE_lower is quite consistent with the increase in 850–500 hPa meridional winds, thus indicating that the enhanced thermal contrast in the lower troposphere plays dominant role in driving the increase in southerly winds along eastern China. One can find, however, that there exists difference between changes in the EASM circulation (nonlinear) and land–sea thermal contrast (linear). We speculate that the main reason for this difference is likely that there exists a positive local feedback between the monsoon circulation and precipitation changes. Dynamically, because of the flat topography in East Asia, the EASM circulation is mainly driven by the low-level land–sea thermal contrast, where the meridional airflows dominate. With global warming, precipitation will increase, and southerly winds will increase due to the increasing low-level land-sea thermal contrast. The increased southerly wind, along with increase of low-level moisture due to large-scale moisture transport and global sea surface temperature warming, causes the strengthened precipitation and ascending motion. The diabatic heating will increase and further enhance the land-sea thermal contrast in the EASM region and then

**Table 3**

Changes (%/°C) in Average Precipitable Water (EASM-Prw), Precipitation (EASM-Pr), 850-hPa Meridional Wind (EASM-V-850 hPa), 500-hPa Vertical Ascending Motion (EASM-500 hPa Omega), and Static Stability (Potential Temperature \(\theta_{200-300 hPa} - \theta_{1000-850 hPa}\) EASM-Stability) in the EASM Region (22.5–40°N, 105–120°E) in June-July-August (JJA) When the GMST Increases by 2, 3, 4, and 5 °C Above the Preindustrial Level

| Temperature | Change in Prw (%) | Change in Pr (%) | Change in V-850 hPa (%) | Change in Omega (Pa/s) | Change in Stability |
|-------------|------------------|-----------------|-------------------------|-----------------------|--------------------|
| 2 °C        | 7.8              | 3.5             | 4.2                     | 3.1                   | 2.2                |
| 3 °C        | 8.5              | 6.0             | 6.9                     | 9.6                   | 2.4                |
| 4 °C        | 8.5              | 6.1             | 9.9                     | 14.1                  | 2.1                |
| 5 °C        | 8.1              | 5.0             | 14.8                    | 12.4                  | 1.9                |

Note. Changes in the JJA global averages of precipitable water (Global-Prw), precipitation (Global-Pr), 500-hPa vertical ascending motion (Global-500 hPa omega), and static stability (Global-stability).
the EASM circulation. This local positive feedback finally leads to a greater increase of local southerly, ascending motion and precipitation over East Asia. Such a local change, however, hardly affects continental-scale land-sea thermal contrast. As a result, the continent-scale land-sea thermal contrast

Figure 5. Same as Figure 4, but for the land-sea thermal contrast (m) in the upper (a, TEupper) and lower (b, TElower) troposphere for the east-west gradient and GMST.

Figure 6. Smoothed histograms of changes (relative to the current climate) in (a) 850-hPa meridional wind (m/s), (b) precipitation (mm/day), (c) precipitable water (kg/m²), and (d) 500-hPa vertical velocity (Pa/s) in the EASM region (22.5°–40°N, 105°–120°E). Black, purple, gray, green, orange, and red solid lines represent the histograms of the current climate and a GMST increase of 1.5, 2, 3, 4, and 5 °C above the preindustrial level, respectively.
appears increasing linearly with global warming, while the increase of local meridional wind, ascending motion, and precipitation appears nonlinear and at a faster rate.

4.3. Probability Distribution of EASM Metrics in the Future

Figure 6 shows the probability density functions (PDFs) of EASM circulation and precipitation. When the GMST increases by 1.5 °C, all the EASM metrics display very little change. After that, with strengthened global warming, the changes in EASM circulation and water vapor become obvious. The PDFs of the 850-hPa meridional wind (Figure 6a) clearly shift rightward but with little change in shape between the current climate and 5 °C of warming, indicating an increase in the mean value but not the variability of low-level meridional winds. Precipitation (Figure 6b) and atmospheric water vapor content (Figure 6c) shift rightward and spread wider, indicating an increase in both the mean and the variability of these two quantities with warming. The PDFs for 500-hPa vertical velocity (Figure 6d) moved leftward without a clear shape change, thus implying only the enhancement of mean vertical ascending motion.

To better understand water vapor conditions, the 1,000- to 100-hPa vertically integrated water vapor fluxes at four boundaries (western boundary, 22.5–40°N, 105–120°E; eastern boundary, 22.5–40°N, 120°E; southern boundary, 22.5°N, 105–120°E; and northern boundary, 40°N, 105–120°E) of the EASM region are shown in Figure 7. The most significant changes are observed in the increased net inflow at the southern boundary. The outflow of water vapor at the eastern boundary also increases, but the magnitude is smaller than that of the changes at the southern boundary. The changes at the western and northern boundaries are small and have minor effects on the convergence in the region. The PDFs of the water vapor transport at the southern boundary do not display changes in shape. On the other hand, the evaporation in the EASM region does

Figure 7. Smoothed histograms of changes (relative to the current climate) in June-July-August (JJA) 1,000- to 100-hPa integral water vapor flux (kg/m/s/hPa) at the four boundaries of the EASM region (22.5–40°N, 105–120°E). Western boundary: 22.5–40°N, 105°E. Eastern boundary: 22.5–40°N, 120°E. Southern boundary: 22.5°N, 105–120°E. Northern boundary: 40°N, 105–120°E.
not change obviously (not shown). All these results indicate that the increased moisture in the EASM region mainly comes from the enhanced southwesterly airflows at the low latitudes from the oceans.

5. The Relative Contributions of Dynamic and Thermodynamic Components to EASM Precipitation Changes

Based on the simple moisture budget method we use, the EASM precipitation changes can be divided into contributions from the dynamic component \( q \omega \) and thermodynamic component \( \Delta q \omega \). The former denotes the precipitation changes due to changing vertical motion, and the latter indicates the precipitation changes caused by the varying water vapor content. As shown in Figure 8, both components will be enhanced with the GMST increases. The dynamic component will increase by 3.2%/K (0.06 mm/day), 9.7%/K (0.18 mm/day), 14.5%/K (0.29 mm/day), and 13.2%/K (0.30 mm/day) under warming of 1 to 2 °C, 2 to 3 °C, 3 to 4 °C, and 4 to 5 °C, respectively. The thermodynamic component will increase by 6.0%/K (0.10 mm/day), 6.3%/K (0.11 mm/day), 6.1%/K (0.12 mm/day), and 5.7%/K (0.12 mm/day), respectively. The dynamic and thermodynamic components increase at a rate of approximately 0.26 and 0.11 mm/day/degree during 2006–2100, respectively. The ratio of the growth rates of the dynamic processes to those of the thermodynamic processes is approximately 2:1, indicating a dominant role of the dynamic component in the increase in EASM precipitation, while the thermodynamic process plays a secondary role.

Figure 9 shows the EASM precipitation changes and the relative contributions of dynamic and thermodynamic components under different global warming levels. The change in EASM precipitation based on the simple budget method is slightly larger than the change in precipitation from the model. The difference may come from the exaggerated effects of 500-hPa vertical velocity compared with those from the fully vertically integrated budget equation. When the GMST increase is small, the contributions of these two components are quite similar. With a GMST increase of more than approximately 2 °C, the dynamic component contributes more than the thermodynamic component. At the 5.0 °C warming level, the positive contribution of the dynamic component is twice that of the thermodynamic component. The thermodynamic component contributes only approximately 33.1% to the precipitation changes. This result clearly shows that increasing monsoon circulation, including enhanced southerly winds and vertical ascending motion, is the most important factor contributing to the EASM precipitation changes, which is completely different from the projections for South Asian monsoon changes (Christensen et al., 2013). We also use a column-integrated moisture budget method following Hsu et al. (2012) to decompose the precipitation in the EASM region (not shown). We find that the increase of EASM precipitation is mainly from the increased moisture convergence, which is related to enhanced regional ascending motion under global warming. The contribution from the changes in moisture and surface evaporation is relatively small, which is consistent with the results from the simplified equation.

The relative contribution of water vapor and winds to the changes in water vapor flux at four boundaries of the EASM area are also estimated (Figure 10). The changes in water vapor transport can be diagnosed as follows, if the nonlinear term \( <\Delta q \Delta \vec{V}> \) is not considered:
\[ \langle \Delta (q \cdot V) \rangle \approx \langle V \cdot \Delta q \rangle + \langle q \cdot \Delta V \rangle \]

where the brackets denote the vertically integrated water vapor fluxes for 1,000–100 hPa, \( \Delta \) denotes the changes in the values under the future climate relative to the values under the current climate, and \( \bar{q} \) and

Figure 9. Relative contributions of the dynamic and thermodynamic components to the precipitation changes under different global warming levels based on the simplified moisture budget decomposition method. The components are estimated based on the CanESM2 50-run ensemble mean. Light blue, red, blue, and green bars denote the model-simulated precipitation changes (mm/day), diagnostic precipitation changes (\( P \), mm/day), dynamic component changes (\( q \cdot \omega \), mm/day), and thermodynamic component changes (\( q \cdot \Delta V \), mm/day), respectively.

Figure 10. Same as Figure 4, but for the June-July-August (JJA) 1,000- to 100-hPa integral water vapor flux (kg/m/s/hPa) at the four boundaries of the EASM region. (a) The water vapor flux at the western boundary (22.5°–40°N, 105°E) and the GMST changes above the preindustrial level. (b) Same as (a), but for the eastern boundary (22.5°–40°N, 120°E). (c) Same as (a), but for the southern boundary (22.5°N, 105–120°E). (d) Same as (a), but for the northern boundary (40°N, 105–120°E).
$\overline{V}$ denote water vapor and horizontal winds under the current climate, respectively. For the water vapor flux changes at the southern boundary, $<\overline{V} \cdot \Delta q>$ increases by 6.8%/K, 6.8%/K, 6.8%/K, and 5.9%/K under warming of 1 to 2 °C, 2 to 3 °C, 3 to 4 °C, and 4 to 5 °C, respectively, which is almost a linear increase. $<\overline{q} \cdot \Delta \overline{V}>$ increases by 3.7%/K, 5.4%/K, 9.6%/K, and 10.9%/K, respectively, which is a nonlinear increase and quite similar to precipitation changes. This finding shows important roles of monsoon circulation and the moisture transport in the EASM precipitation changes.

We also calculated the convergence of water vapor fluxes at the EASM region. At the current climate, the area averaged 1,000- to 100-hPa integrated water vapor flux show convergence in the EASM area. The convergence increases by 4.5%/K, 9.1%/K, 10.2%/K, and 7.6%/K under warming of 1 to 2 °C, 2 to 3 °C, 3 to 4 °C, and 4 to 5 °C, respectively. This indicates a rapid increase of moisture convergence and its nonlinear relationship with GMST increase.

6. Conclusion

We use large-ensemble runs of CanESM2 to investigate EASM changes under increasing global warming levels. The CanESM2 shows good performance in reproducing basic climatological features of the EASM circulation and precipitation. Based on this model, we build a link between the EASM changes with increasing GMST under 1.5 to 5 °C of warming. The model projections reveal that the intensities of the EASM circulation and precipitation will increase with global warming, which is different from the projection for other monsoon regions. Previous studies have shown that in most monsoon regions, the summer monsoon shows increasing precipitation and decreasing monsoon circulation (IPCC, 2013; Wang et al., 2013; Zhou et al., 2018).

With global warming, the EASM precipitable water will increase quasi-linearly, while 850-hPa meridional wind, precipitation and 500-hPa vertical ascending motion will be enhanced nonlinearly. The increased EASM circulation is mainly driven by the enhanced thermal contrast in the lower troposphere, while the thermal contrast in the upper troposphere is almost unchanged with warming. The PDF analyses show that EASM precipitation and precipitable water will increase in both mean value and variability, which may result in more extreme weather in the future. The rapid increase in northward moisture transport at the southern boundary is the dominant contributor to the moisture convergence and precipitation change in the EASM region.

A simplified water vapor budget method is used to estimate the relative contributions of dynamic and thermodynamic components to future EASM precipitation changes. When the GMST increases by less than 2 °C, the positive contributions of dynamic and thermodynamic components are quite similar. With continuous warming, the effect of the dynamic process gradually becomes a dominant factor. When the warming is 5 °C, the positive contribution of the dynamic component is almost twice as large as that of the thermodynamic component. These results shed light on the link between EASM changes and global warming levels and provide useful information for developing strategies for climate change policy in East Asia, which is the most populous region in the world.

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