

Research Article

High-Resolution Climate Simulations in the Tropics with Complex Terrain Employing the CESM/WRF Model

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This study evaluates the high-resolution climate simulation system CESM/WRF composed of the global climate model, Community Earth System Model (CESM) version 1, and the mesoscale model, Weather Research and Forecasting Model (WRF), for simulating high-resolution climatological temperature and precipitation in the tropics with complex terrain where temperature and precipitation are strongly inhomogeneous. The CESM/WRF climatological annual and seasonal precipitation and temperature simulations for years 1980–1999 at 10 km resolution for Sumatra and nearby regions are evaluated using observations and the global climate reanalysis ERA-Interim (ERA). CESM/WRF simulations at 10 km resolution are also compared with the downscaled reanalysis ERA/WRF at 10 km resolution. Results show that while temperature and precipitation and accuracies of simulations are significantly improved by dynamically downscaling CESM using WRF. CESM/WRF can simulate locations of very cold temperature at mountain peaks well. The high-resolution climate simulation system CESM/WRF can provide useful climate simulations at high resolution for Sumatra and nearby regions. CESM/WRF for climate projections at high resolution agree well with ERA/WRF. This suggests the use of CESM/WRF for climate projections at high resolution for Sumatra and nearby regions.

1. Introduction

Climate change is an important threat to humanity. The global average temperature has been rising and has been projected to increase up to $2-5^{\circ}$ C by the end of the twenty-first century [1]. Global warming causes glacier retreat, sea level rise, extreme weather intensification, and changes in precipitation amount and pattern [2]. Accurate numerical systems for climate simulation and projection at sufficiently high resolution are required for effective climate change mitigation and adaptation, which will improve resilience of the society.

To obtain climate simulations and projections, global climate models (GCMs), which model physical processes of

atmosphere, ocean, land surface, and cryosphere by taking into the account of different scenarios of increasing greenhouse gases, can be employed [1]. However, the coarse resolutions of GCMs are generally not sufficient to provide useful climate change information and impacts for a specific area, particularly where climate and weather are inhomogeneous, e.g., the areas with complex terrain and in the tropics where precipitation is strongly driven by convection at finer scales than those can be resolved by GCMs.

Indonesia's Sumatra Island is in the tropics with the equator running through it and is one of the rainiest areas on Earth. Weather-related disasters, i.e., floods, landslides, and severe storms often affect Sumatra. Since Sumatra has complex terrain with high mountains and volcanoes and temperature and precipitation are very inhomogeneous, numerical systems for simulating and projecting climate at high resolution are required for appropriately adapting to climate change and reducing climate change impacts. Although there are some previous climate simulation studies for Southeast Asia [3, 4] and for Indonesia [5], their simulations at 60 km resolution are too coarse to resolve climatological temperature and precipitation of Sumatra, as the results from this study will clearly show.

High-resolution climate simulations and projections can be obtained by dynamically downscaling GCM outputs using a mesoscale model [6, 7]. However, such previous studies for Sumatra do not exist. Since climate is different for different areas and GCMs and mesoscale models perform differently for different areas, this study is the work towards the main goal of developing a numerical system that is capable of providing useful high-resolution climate simulations for Sumatra. If the system performs well, this study could be extended to the development of a numerical system for providing climate projections at high resolution for Sumatra.

The Community Earth System Model (CESM) version 1 [8] is a GCM participating in the fifth Coupled Model Intercomparison Project (CMIP5) [9]. CESM climate simulations and projections have been widely used for climate studies [10–13]. Since CESM's three-dimensional outputs are publicly available and are ready to be used to drive a mesoscale model, CESM is employed in this study. Several mesoscale models are publicly available, e.g., the fifthgeneration NCAR/Penn State Mesoscale Model (MM5) [14, 15] and the next-generation Weather Research and Forecasting Model (WRF) [16, 17]. WRF is employed in this study.

The numerical climate simulation system employed in this study is composed of CESM and WRF and is called CESM/WRF. Although the preliminary study [18] has evaluated the performance of CESM/WRF for simulating climatological temperature and precipitation for Sumatra by comparing CESM/WRF simulations for years 1980–1999 with observation and reanalysis datasets, it has evaluated only simulated annual temperature and precipitation and the highest resolution of observation and reanalysis datasets used for evaluation is only 0.5°. The performance of CESM/ WRF is evaluated in further details in this study and is compared with that of the original CESM.

Several climate simulation studies [19–21] have employed WRF to downscale the ERA-Interim reanalysis dataset (ERA) [22]. Soares et al.[19] have evaluated the performances for simulating climatological temperature and precipitation of ERA downscaled using WRF (ERA/ WRF) and the original ERA using observations from dense ground stations in Portugal and have shown that ERA/ WRF performs better than ERA, particularly for highresolution precipitation simulations in the rainiest regions with crucial orographic enhancement. Huang and Gao [20] have evaluated the performances for simulating climatological temperature and precipitation of WRF dynamical downscaling forced by ERA and the National Centers for Environmental Prediction (NCEP) Global Final Analysis (FNL) and have shown that they perform very differently.

Observations for temperature and precipitation at 10 km resolution or better for the 20-year period of 1980–1999 and dense ground stations in Sumatra do not exist [23]. Sparse ground stations cannot provide accurate information about spatial distributions of temperature and precipitation, particularly in the tropics with complex terrain, where temperature and precipitation are very inhomogeneous. From results of [19], ERA dynamically downscaled using WRF should provide reasonable high-resolution temperature and precipitation for evaluating CESM/WRF-simulated climatological temperature and precipitation at 10 km resolution, particularly for the regions with the strong orographic effect. In this study, ERA is dynamically downscaled using WRF to obtain downscaled reanalysis at 10 km resolution (ERA/ WRF). CESM/WRF-simulated climatological temperature and precipitation at 10 km resolution are compared with those of ERA/WRF. The comparison of CESM/WRF and ERA/WRF also benefits climate projection studies. Since ERA does not provide climate projection while CESM does, if CESM/WRF performs comparably or better than ERA/ WRF, it will gain confidence of using CESM/WRF for climate projections.

Section 2 describes the research methodology employed in this study, which includes the study area, observation and reanalysis datasets, the high-resolution numerical climate simulation system CESM/WRF, and the downscaled reanalysis ERA/WRF. The evaluation results are presented in Section 3. The study is summarized and concluded in Section 4.

2. Research Methodology

2.1. Study Area. Figure 1 shows the study area, which covers Indonesia's Sumatra Island and part of Java Island, Malaysia, and Singapore. Sumatra is one of the major islands in Indonesia with the equator crossing near its center. It stretches along a diagonal northwest-southeast axis in western Indonesia with a total land area of about 473,606 km². Sumatra and Java islands have complex terrain with several high mountains and volcanoes stretching along the west coast of the island due to the Sunda Megathrust where the Indo-Australian plate subducts beneath the Eurasian plate. Malaysia also has high mountains near its center.

The climate of Sumatra is tropical with hot and humid weather. There are 2 major seasons, including the rainy season approximately from October to April of each year and the dry season approximately from May to September of each year. Sumatra has significant precipitation amount throughout the year. Precipitation is mostly convective and varies greatly from area to area. Intense convective precipitation could lead to landslides and floods. Sumatra has often been affected by floods, landslides, and severe storms. High-resolution numerical climate simulations and projections are hence important for better understanding of climate change and its potential impacts for Sumatra.



FIGURE 1: (a) Coverages of WRF's 2 co-centered domains employed in this study. (b) Topography (m) above mean sea level of the WRF's inner domain

2.2. Observation and Reanalysis Datasets. Four observation datasets including the University of Delaware Air Temperature and Precipitation version 3.01 (UD) [24], the University of East Anglia Climatic Research Unit TS3.10 (CRU) [25], the Global Precipitation Climate Center (GPCC) [26], and the NOAA Climate Prediction Center Unified Gauge-Based Analysis of Global Daily Precipitation (CPC) [27] and the ERA-Interim global atmospheric reanalysis dataset (ERA) [22] covering years 1980–1999 are employed in this study for evaluating CESM and CESM/ WRF climatological simulations.

UD monthly global gridded data for air temperature and precipitation are available from 1900 to 2010 and are produced using data both from the Global Historical Climate Network and the archive of Legates and Willmott. CRU monthly global gridded data for air temperature and precipitation are available from 1901 to 2009 and are produced using daily or subdaily data by National Meteorological Services and other external agents. GPCC monthly global gridded precipitation data are available from 1901 to present and are produced using quality-controlled data from 67,200 global stations. CPC daily global gridded precipitation data are available from 1979 to present and are produced using quality-controlled gauge reports from over 30,000 global stations with consideration of orographic effects. UD, CRU, GPCC, and CPC are available only over land and are on regular 0.5° grids.

ERA reanalysis is produced using the four-dimensional variational analysis (4D-Var) system that relies on both observations and model-based forecasts and is available from 1979 to present. ERA is available for both land and sea

and is on a regular 0.75° grid with 60 vertical levels from the surface up to 0.1 mb. ERA outputs are available every 6 h, i.e., 00, 06, 12, and 18Z and can be used as initial and boundary conditions for WRF. ERA precipitation is computed using accumulated precipitation available every 12 h. This study treats ERA reanalysis data as observations.

2.3. CESM/WRF Climate Simulations. The numerical climate simulation system used in this study is composed of the global climate model Community Earth System Model (CESM) version 1 [8] and the next-generation mesoscale numerical weather prediction model Weather Research and Forecasting (WRF) Model [16, 17]. CESM has been developed by the National Center for Atmospheric Research (NCAR) and is a fully-coupled global climate model (GCM). It is a GCM that participates in the fifth Coupled Model Intercomparison Project (CMIP5). CESM outputs are at ~1-degree resolution with 26 pressure levels and are available every 6 h, including 00, 06, 12, and 18Z.

WRF has been widely employed for research and operations. There are several WRF versions. This study employs WRF with the Advanced Research WRF core version 3.7.1. WRF's initial and boundary conditions are CESM outputs. Figure 1 shows coverages of WRF's 2 co-centered domains employed in this study. The one-way nesting strategy is used. WRF's vertical levels are terrain following. Each domain has 35 vertical levels extending from the ground up to 50 mb. The outer domain has the size of 100×100 grid points with 30 km resolution and covers latitudes of $13^{\circ}S-13^{\circ}N$ and longitudes of $87^{\circ}E-114^{\circ}E$. The inner domain

has the size of 190×190 grid points with 10 km resolution and covers latitudes of 8.5° S- 8.5° N and longitudes of 92.5° E- 110° E. The spectral nudging is employed for the outer domain for altitudes above planetary boundary layer so that WRF simulations at large scales are consistent with CESM outputs. The wavenumber for spectral nudging is set to 3, which corresponds to the adjustment only for waves greater than ~1,000 km [28]. The frequency of the adjustment is 24 h.

Several WRF physics options are available. Surussavadee and Aonchart [29] have found that the combination of the WRF Double-Moment 6-class microphysics scheme [30] and the Betts–Miller–Janjic cumulus parameterization scheme [31] provides the best agreement between highresolution weather forecasts and satellite observations for Thailand and nearby regions. Surussavadee [17] has found that the combination of the Bretherton and Park (UW) planetary boundary layer scheme [32], the Revised MM5 Monin-Obukhov surface layer scheme [33], and the Unified Noah land surface model [34] provides the best agreement between simulated near-surface winds and ground measurements for Thailand. The WRF physics options employed in this study follow the best physic options found in References [17, 29].

Sumatra's climate for 20 y covering 1980–1999 is simulated by CESM/WRF. Two separate WRF integrations for each decade are used in order to optimize computational resources and time. The spin up time of 1 y is employed. CESM/WRF outputs from the inner domain at 10 km resolution are employed in this study. Since CESM/WRF outputs are at 10 km resolution, whereas all observation datasets, i.e., CPC, CRU, GPCC, and UD are at 0.5° resolution and the ERA reanalysis is at 0.75° resolution, to generate CESM/WRF simulations at a resolution comparable to those of observations and reanalysis; CESM/WRF simulations at 10 km resolution are convolved with a Gaussian function having full width at half maximum (FWHM) of 50 km before they are evaluated. All observations and reanalysis are bilinearly interpolated on the grid of the CESM/WRF inner domain. The simulation performances of CESM and CESM/WRF are evaluated using the performance metrics, including root-mean-squared errors (RMSEs), mean errors (MEs), which is E[observations simulations], and correlation coefficients (CCs) of simulations and observations.

2.4. ERA/WRF Climate Simulations. The ERA-Interim global atmospheric reanalysis dataset (ERA) [22] is dynamically downscaled using WRF to obtain downscaled reanalysis at 10 km resolution and is called ERA/WRF. The WRF domain configurations and physics options and the strategy for downscaling employed for ERA/WRF are the same as those employed for CESM/WRF. ERA/WRF outputs from the inner domain at 10 km resolution are employed.

3. Results

3.1. Evaluation of Climatological Temperature Simulated by CESM and CESM/WRF Using Observations and Reanalysis.

Figure 2 compares 20-year average temperature (°C) simulated by the original CESM and the WRF-downscaled CESM (CESM/WRF) with CRU, UD, and ERA and the average of CRU, UD, and ERA. All are on the same CESM/ WRF inner grid. CESM/WRF in this section is the original 10 km resolution CESM/WRF convolved with a Gaussian function having full width at half maximum (FWHM) of 50 km. Figure 2 shows that all observations, including CRU, UD, and ERA, are different from one another. UD appears to have the highest spatial resolution among the three observations, whereas the spatial resolution of ERA is the lowest. CRU's temperature over eastern Sumatra is obviously higher than that of UD and ERA. Although all observations show the cold temperature patterns over high mountains along the west coasts of Sumatra and Java islands and in the center areas of Malaysia, only UD can resolve cold spots at mountain peaks.

Simulated temperature of the original CESM and CESM/ WRF is very different for both pattern and intensity. CESM's temperature over sea is obviously higher than all observations and CESM/WRF. CESM's temperature over land is also very different from all observations and CESM/WRF. CESM/WRF agrees with observations much better than CESM does, while CESM obviously cannot resolve temperature for high mountains along the west coasts of Sumatra and Java islands; CESM/WRF does it well. CESM/ WRF can also simulate cold spots over mountain peaks well. The locations of CESM/WRF's cold spots agree well with those of UD. CESM/WRF's temperature over sea is obviously improved over that of CESM. Downscaling CESM using WRF significantly improves the simulated climatological temperature for both land and sea.

Figure 3(a) shows the scatter plots comparing annual average temperature (°C) for individual years of 1980-1999 simulated by CESM and CESM/WRF with the average of CRU, UD, and ERA. Points in the scatter plots are samples of all grid cells of the CESM/WRF inner domain. Simulated annual average temperature for the 20 y of CESM/WRF is more accurate than that of CESM and agrees well with observations. Downscaling CESM using WRF improves correlation coefficient (CC) between simulations and observations from 0.62 to 0.83. CESM's simulated temperature at the low end appears to be clipped at ~24°C. CESM also overestimates temperatures higher than ~28°C. CESM/WRF does not have these two issues. Figure 3(b) shows scatter plots comparing 20-y average temperature (°C) simulated by CESM and CESM/WRF with the average of CRU, UD, and ERA. Results are similar to those shown in Figure 3(a). CESM/WRF 20 y average temperature simulations are obviously more accurate than CESM simulations. Downscaling CESM using WRF improves correlation coefficient between simulations and observations from 0.66 to 0.87.

Table 1 shows RMSEs, MEs (E[observations – simulations]), and CCs for annual average temperature (°C) for 20 y of 1980–1999 simulated by CESM and CESM/WRF evaluated using the average of CRU, UD, and ERA for land only, sea only, and both land and sea. Boldface highlights the model that performs best for each performance metric. Table 2 shows the same as that shown in Table 1, but



FIGURE 2: Comparisons of 20-y average temperature (°C) simulated by CESM and CESM/WRF with CRU, UD, and ERA and the average of CRU, UD, and ERA. CESM and ERA are at 1° and 0.75° resolutions, respectively. CRU and UD are at 0.5° resolution. CESM/WRF is at 50 km resolution.

for 20-y average temperature. Results are consistent with those shown in Figures 2 and 3. Accuracies of CESM/WRF simulations are significantly better than those of CESM simulations for both land and sea. Dynamic downscaling improves overall RMSE from 1.69 to 1.03° C for annual average temperature for 20 y and from 1.62 to 0.94° C for 20-y average temperature. ME reduces from -1.18 to -0.57° C. CC improves from 0.62 to 0.83 for annual average temperature for 20 y and everage temperature for 20 y average temperature for 20 y average temperature.

3.2. Comparison of High-Resolution Climatological Temperature Simulated by CESM/WRF and ERA/WRF. Climatological temperatures simulated by CESM/WRF and ERA/WRF at 10 km resolution are compared in this section. Figure 4 shows CESM/WRF- and ERA/WRF-simulated 20-y average temperature simulations (°C). The pattern and intensity of CESM/WRF-simulated 20-y average temperature agree well with those of ERA/WRF. Both CESM/WRF and ERA/WRF show low temperature pattern along the west coasts of Sumatra and Java and in the middle of Malaysia. Both also show fine-scale cold spots over mountain peaks, which are consistent with UD shown in Figure 2. Their areas of high temperature also agree well. Comparison of ERA/ WRF with UD shows that dynamic downscaling employing WRF not only improves CESM simulations but also improves ERA reanalysis.

Figure 5 shows scatter plots comparing CESM/WRF and ERA/WRF for annual average temperature (°C) for 20 y and

20-y average temperature (°C). CESM/WRF and ERA/WRF agree well for both annual average temperature for 20 y and 20-y average temperature with high CCs of 0.97 and 1.00, respectively.

Table 3 shows the root-mean-squared differences (RMSDs), mean differences (MDs), which is E[ERA/WRF - CESM/WRF], and CCs of CESM/WRF and ERA/WRF for simulated annual average temperature (°C) for 20 y and 20-y average temperature (°C) for land only, sea only, and both land and sea. CESM/WRF and ERA/WRF climatological temperature agree well for both land and sea. Overall RMSDs for annual average temperature for 20 y and 20-y average temperature are 0.44 and 0.11°C, respectively. MDs between CESM/WRF and ERA/WRF are almost zero. CCs between CESM/WRF and ERA/WRF for annual average temperature for 20 y and 20-y average temperature are 0.97 and 1.00, respectively.

3.3. Evaluation of Climatological Precipitation Simulated by CESM and CESM/WRF Using Observations and Reanalysis. The accuracies of CESM- and CESM/WRF-simulated climatological precipitation are evaluated using observations and reanalysis. CESM/WRF in this section is the original 10 km resolution CESM/WRF convolved with a Gaussian function having full width at half maximum (FWHM) of 50 km. Figure 6 compares 20-y average annual precipitation (mm/y) simulated by CESM and CESM/WRF with CPC, CRU, GPCC, UD, and ERA and the average of CPC, CRU, GPCC, UD, and ERA. All are on the same CESM/WRF inner grid.



FIGURE 3: Scatter plots comparing CESM and CESM/WRF simulations with the average of CRU, UD, and ERA for (a) annual average temperature ($^{\circ}$ C) for 20 y and (b) 20-y average temperature ($^{\circ}$ C). CESM and ERA are at 1 $^{\circ}$ and 0.75 $^{\circ}$ resolutions, respectively. CRU and UD are at 0.5 $^{\circ}$ resolution. CESM/WRF is at 50 km resolution.

TABLE 1: RMSEs, MEs (E[observations – simulations]), and CCs of simulations and observations for CESM and CESM/WRF-simulated annual average temperature (°C) for 20 y evaluated using the average of CRU, UD, and ERA for land only, sea only, and both land and sea, where CESM/WRF is at 50 km resolution.

Metric	CESM			CESM/WRF		
	Land	Sea	All	Land	Sea	All
RMSE	1.49	1.74	1.69	0.96	1.05	1.03
ME	-0.12	-1.51	-1.18	0.23	-0.82	-0.57
CC	0.31	0.29	0.62	0.90	0.23	0.83

TABLE 2: RMSEs, MEs (E[observations – simulations]), and CCs of simulations and observations for CESM and CESM/WRF-simulated 20-y average temperature (°C) evaluated using the average of CRU, UD, and ERA for land only, sea only, and both land and sea, where CESM/WRF is at 50 km resolution.

Metric		CESM		CESM/WRF		
	Land	Sea	All	Land	Sea	All
RMSE	1.45	1.67	1.62	0.92	0.95	0.94
ME	-0.12	-1.51	-1.18	0.23	-0.82	-0.57
CC	0.32	0.39	0.66	0.92	0.44	0.87

Boldface highlights the model performing best for each performance metric.

Boldface highlights the model performing best for each performance metric.

Comparison of the observation and reanalysis datasets shows some differences due to the sources and methods employed for different datasets and their spatial resolutions. Comparison of observations over Malaysia shows that CRU has high precipitation at the center of Malaysia and surrounding areas, CPC has high precipitation along the east coast, GPCC and UD have high precipitation along the east and west coasts, and ERA has high precipitation along the west coast. Only ERA has precipitation data over the sea. Three main precipitation patterns consistent with most observation datasets include: (1) high precipitation over land along the west coasts of Sumatra and Java islands and lower precipitation over land along the east coasts, (2) high precipitation over the Indian Ocean to the west of Sumatra, and



FIGURE 4: Comparisons of CESM/WRF and ERA/WRF 20-y average temperature (°C). Both CESM/WRF and ERA/WRF are at 10 km resolution.



FIGURE 5: Scatter plots comparing CESM/WRF and ERA/WRF for (a) annual average temperature (°C) for 20 y and (b) 20-y average temperature (°C). Both CESM/WRF and ERA/WRF are at 10 km resolution.

TABLE 3: RMSDs, MDs (E[ERA/WRF - CESM/WRF]), and CCs of CESM/WRF and ERA/WRF for simulated annual average temperature (°C) for 20 y and 20-y average temperature (°C) for land only, sea only, and both land and sea, where both CESM/WRF and ERA/WRF are at 10 km resolution.

Metric	Annual average temperature for 20 y			20 y average temperature		
	Land	Sea	All	Land	Sea	All
RMSD	0.35	0.47	0.44	0.11	0.10	0.11
MD	0.06	0.01	0.02	0.06	0.01	0.02
CC	0.99	0.34	0.97	1.00	0.92	1.00

(3) low precipitation over the Pacific Ocean to the east of Sumatra and Malaysia.

The 20-y average annual precipitation simulated by CESM contradicts the observations and does not have any of the 3 main precipitation patterns shown in observations.

CESM has high precipitation over land in northwest Sumatra, all regions of Malaysia, southeast Sumatra, and along the east coast of Java. CESM has low precipitation over the Indian Ocean to the west of Sumatra and high precipitation over the Pacific Ocean to the east of Sumatra and Malaysia.

The pattern, intensity, and spatial resolution of 20-y average annual precipitation simulated by CESM and CESM/WRF are very different. The resolution and accuracies of simulated precipitation are significantly improved by the dynamically downscaling method employed in this study. CESM/WRF can simulate the 3 main precipitation patterns shown in the observations well. Its high precipitation at the center of Malaysia and surrounding areas is also consistent with that of CRU. The main difference between CESM/WRF and observations is the higher precipitation amount of CESM/WRF over high mountains along the west coasts of Sumatra and Java



FIGURE 6: Comparisons of 20-y average annual precipitation (mm/y) simulated by CESM and CESM/WRF with CPC, CRU, GPCC, UD, and ERA and the average of CPC, CRU, GPCC, UD, and ERA. CESM and ERA are at 1° and 0.75° resolutions, respectively. CPC, CRU, GPCC, and UD are at 0.5° resolution. CESM/WRF is at 50 km resolution.

islands. This could be due to (1) the significantly higher resolution of CESM/WRF compared to those of all observations, (2) errors in CESM, and (3) errors in WRF physics.

Figure 7 compares CESM- and CESM/WRF-simulated 20-y average seasonal precipitation for the rainy season, i.e., from October to April, with CPC, CRU, GPCC, UD, and ERA and the average of CPC, CRU, GPCC, UD, and ERA. Figure 8 compares CESM- and CESM/WRF-simulated 20-y average seasonal precipitation for the dry season, i.e., from May to September, with CPC, CRU, GPCC, UD, and ERA and the average of CPC, CRU, GPCC, UD, and ERA. Results shown in Figures 7 and 8 are similar to those for the simulated 20 y annual precipitation for the two seasons has the 3 main precipitation patterns, (2) the precipitations, and (3) CESM/WRF can

simulate the 3 precipitation patterns well and performs significantly better than CESM. CESM/WRF-simulated precipitation for the two seasons over mountains along west coasts of Sumatra and Java islands are higher than observations.

The annual precipitation (mm/y) for individual years from 1980 to 1999 simulated by CESM and CESM/WRF is compared with the average of all five observation datasets using scatter plots in Figure 9(a). It is important to note that precipitation evaluation using scatter plots is difficult to get good agreement since different observation and reanalysis datasets also have differences among themselves. Downscaling CESM using WRF significantly improves the agreement of simulated annual precipitation with observations, where the correlation coefficient (CC) of simulations and observations improves from -0.14 for the original CESM to 0.47 for CESM/WRF. The range of CESM/WRF annual precipitation is larger than that of both CESM and



FIGURE 7: Comparisons of 20-y average seasonal precipitation for the rainy season (mm/season) simulated by CESM and CESM/WRF with CPC, CRU, GPCC, UD, and ERA and the average of CPC, CRU, GPCC, UD, and ERA. CESM and ERA are at 1° and 0.75° resolutions, respectively. CPC, CRU, GPCC, and UD are at 0.5° resolution. CESM/WRF is at 50 km resolution.

observations. The CESM/WRF's larger range is mainly due to its higher spatial resolution.

The 20-y average annual precipitation (mm/y) simulated by CESM and CESM/WRF is compared with the average of all five observation datasets in Figure 9(b). CESM/WRF is obviously more accurate than CESM. The dynamic downscaling significantly improves CC of simulations and observations from -0.38 for the original CESM to 0.69 for CESM/WRF. The increases of CCs in both Figures 9(a) and 9(b) are consistent with results shown in Figure 6, where the precipitation pattern of CESM/WRF agrees much better with observations.

Tables 4 and 5 show the performance metrics of annual precipitation for individual years of 1980–1999 and 20 y average annual precipitation, respectively, simulated by CESM and CESM/WRF evaluated using the average of CPC, CRU, ERA, GPCC, and UD for land only, sea only,

and both land and sea. Boldface highlights the model performing best for each performance metric. Accuracies for both annual precipitation for individual years and 20-y average annual precipitation are significantly improved by dynamical downscaling CESM using WRF. Overall CC significantly increases from -0.14 to 0.47 for annual precipitation for 20 y and from -0.38 to 0.69 for 20 y average annual precipitation. Overall RMSE improves from 922.32 to 904.15 mm/y for annual precipitation for 20 y and from 728.92 to 581.61 for 20-y average annual precipitation. Overall ME significantly reduces by ~78%. CESM/WRF performs worse than CESM in terms of RMSE and ME over land. This is consistent with CESM/WRF's higher precipitation amount over high mountains along the west coasts of Sumatra and Java islands in Figure 6. The performance of CESM/WRF to simulate climatological precipitation pattern over land is much better than that of



FIGURE 8: Comparisons of 20-y average seasonal precipitation for the dry season (mm/season) simulated by CESM and CESM/WRF with CPC, CRU, GPCC, UD, ERA, and the average of CPC, CRU, GPCC, UD, and ERA. CESM and ERA are at 1° and 0.75° resolutions, respectively. CPC, CRU, GPCC, and UD are at 0.5° resolution. CESM/WRF is at 50 km resolution.



FIGURE 9: Continued.



FIGURE 9: Scatter plots comparing CESM and CESM/WRF simulations with the average of CPC, CRU, GPCC, UD, and ERA for (a) annual precipitation (mm/y) for 20 y and (b) 20-y average annual precipitation (mm/y). CESM/WRF is at 50 km resolution.

TABLE 4: RMSEs, MEs (*E*[observations – simulations]), and CCs of simulations and observations for CESM and CESM/WRF-simulated annual precipitation (mm) for 20 y evaluated using the average of CPC, CRU, ERA, GPCC, and UD for land only, sea only, and both land and sea, where CESM/WRF is at 50 km resolution.

Metric	CESM			CESM/WRF		
	Land	Sea	All	Land	Sea	All
RMSE	659.13	990.53	922.32	1,061.87	848.69	904.15
ME	-105.82	371.76	257.78	-341.19	182.19	57.28
CC	-0.02	-0.14	-0.14	0.29	0.55	0.47

Boldface highlights the model performing best for each performance metric.

TABLE 5: RMSEs, MEs (*E*[observations – simulations]), and CCs of simulations and observations for CESM and CESM/WRF simulated 20-y average annual precipitation (mm) evaluated using the average of CPC, CRU, ERA, GPCC, and UD for land only, sea only, and both land and sea, where CESM/WRF is at 50 km resolution.

Metric	CESM			CESM/WRF		
	Land	Sea	All	Land	Sea	All
RMSE	471.59	792.57	728.92	940.19	408.92	581.61
ME	-105.82	371.76	257.78	-341.19	182.19	57.28
CC	-0.29	-0.36	-0.38	0.35	0.88	0.69

Boldface highlights the model performing best for each performance metric.

CESM. This can be seen from the improvement of CC from -0.29 for CESM to 0.35 for CESM/WRF.

3.4. Comparison of High-Resolution Climatological Precipitation Simulated by CESM/WRF and ERA/WRF. CESM/WRF-simulated climatological precipitation at 10 km resolution is compared with ERA/WRF at 10 km resolution. Top to bottom rows of Figure 10 compare CESM/WRF and ERA/WRF for 20-y average annual precipitation (mm/y) and 20-y average seasonal precipitation for rainy and dry seasons, respectively. CESM/WRF- and ERA/WRF-

simulated 20-y average annual precipitation (mm/y) agree well for both precipitation pattern and intensity, i.e., precipitation is high along west coasts of Sumatra and Java islands, in the middle of Malaysia, and over the Indian Ocean to the west of Sumatra, and precipitation is low along the east coasts of Sumatra and Java islands, in the south of Malaysia, and over the Pacific Ocean to the east of Sumatra and Malaysia. The locations of CESM/WRF's precipitation peaks also agree well with those of ERA/WRF. Their main difference is over the Pacific Ocean to the east of Sumatra and Malaysia where ERA/WRF has lower precipitation. Seasonal precipitation of CESM/WRF and ERA/ WRF agree well for both rainy and dry seasons. Their main difference is over the Indian Ocean to the west of Sumatra and over the Pacific Ocean to the east of Sumatra and Malaysia, where CESM/WRF has higher precipitation.

The scatter plots in Figure 11 compare CESM/WRFsimulated annual precipitation for 20 y and 20-y average annual precipitation with ERA/WRF. CESM/WRFsimulated annual precipitation and its long-term average agree well with ERA/WRF with CCs of 0.73 and 0.95, respectively. CESM/WRF-simulated 20-y average annual precipitation is biased higher than ERA/WRF for annual precipitation lower than ~2,000 mm/y and agrees well with ERA/WRF, otherwise particularly for high precipitation. This is consistent with results shown in the top row of Figure 10.

The scatter plots in Figure 12 compare CESM/WRFsimulated seasonal precipitation (mm) for years 1980–1999 and 20-y average seasonal precipitation for the rainy and dry seasons with ERA/WRF. Results are consistent with image comparisons in Figure 10. CESM/WRF simulations agree well with ERA/WRF for both seasons with high CCs. CCs between CESM/WRF and ERA/WRF 20-y average seasonal precipitation are as high as 0.96 and 0.95 for rainy and dry seasons, respectively. CESM/WRF 20-y average seasonal precipitation is biased higher than ERA/WRF for precipitation lower than ~2,000 mm.



FIGURE 10: Top to bottom: comparisons of CESM/WRF and ERA/WRF for 20-y average annual precipitation (mm/y) and 20-y average seasonal precipitation (mm/season) for the rainy and dry seasons, respectively. Both CESM/WRF and ERA/WRF are at 10 km resolution.

Table 6 shows the root-mean-squared differences (RMSDs), mean differences (MDs), which is *E*[ERA/WRF – CESM/WRF], and CCs of CESM/WRF and ERA/WRF for simulated precipitation for 20 y and 20-y average precipitation for annual and rainy and dry seasons. CESM/WRF simulations are highly correlated with ERA/WRF for both annual and seasonal precipitation. CCs for 20 y annual and seasonal average precipitation are greater than or equal to 0.95. To get the idea about the size of RMSEs and MEs, numbers in the brackets in Table 6 are in percentages of the mean of ERA/WRF. RMSDs are 18.02, 17.08, and 24.94% of the mean of ERA/WRF for 20-y average annual precipitation and 20-y average seasonal precipitation for rainy and dry

seasons, respectively. CESM/WRF precipitation simulations are biased higher than ERA/WRF. MDs are -13.10, -10.32, and -19.06% of the mean of ERA/WRF for 20-y average annual precipitation and 20-y average seasonal precipitation for rainy and dry seasons, respectively.

4. Summary and Conclusion

The performance of a high-resolution climate simulation system CESM/WRF developed to be used for Sumatra and nearby regions is evaluated. CESM/WRF is composed of a mesoscale model WRF and outputs from the global climate model CESM used for initial and boundary conditions.



FIGURE 11: Scatter plots comparing CESM/WRF and ERA/WRF for (a) annual precipitation (mm/y) for 20 y and (b) 20-y average annual precipitation (mm/y). Both CESM/WRF and ERA/WRF are at 10 km resolution.



FIGURE 12: Scatter plots comparing CESM/WRF and ERA/WRF seasonal precipitation for 20 y (mm/season; left column) and 20-y average seasonal precipitation (mm/season; right column) for (a) rainy and (b) dry seasons. Both CESM/WRF and ERA/WRF are at 10 km resolution.

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Metric		Precipitation for 20 y	r	20 y average precipitation			
	Annual	Rain season	Dry season	Annual	Rain season	Dry season	
RMSD	846.71 (36.41)	627.55 (39.54)	606.12 (58.61)	419.08 (18.02)	271.03 (17.08)	257.93 (24.94)	
MD	-304.58 (-13.10)	-163.79 (-10.32)	-197.10 (-19.06)	-304.58 (-13.10)	-163.79 (-10.32)	-197.10 (-19.06)	
CC	0.73	0.71	0.62	0.95	0.96	0.95	

TABLE 6: RMSDs, MDs (*E*[ERA/WRF – CESM/WRF]), and CCs of CESM/WRF and ERA/WRF for simulated precipitation for 20 y and 20-y average precipitation for annual and rainy and dry seasons, where both CESM/WRF and ERA/WRF are at 10 km resolution.

RMSDs and MDs in the brackets are in percentages of the mean of ERA/WRF.

CESM/WRF-simulated temperature and precipitation at 10 km resolution for Sumatra and nearby regions from 1980 to 1999 are evaluated using 4 observation datasets, including CPC, CRU, GPCC, UD, and the ERA reanalysis dataset treated in this study as an observation dataset. Since all observations have resolutions lower than 10 km and dense ground stations in Sumatra do not exist, the CESM/WRF-simulated climatological temperature and precipitation at 10 km resolution are compared with the downscaled reanalysis ERA/WRF at 10 km resolution.

Although different observation datasets have some differences among themselves for both climatological temperature and precipitation, there are patterns consistent for most observation datasets. While CESM contradicts all observation patterns for both temperature and precipitation, CESM/WRF can simulate all patterns well; CESM/WRF can simulate all patterns well. CESM/WRF can also resolve locations of very cold temperature at mountain peaks consistent with those of UD. Downscaling CESM using WRF significantly improves resolution and accuracies of the simulations. The main discrepancy between CESM/WRF-simulated precipitation and observations is CESM/WRF's higher precipitation over high mountains along the west coasts of Sumatra and Java islands and could be due to the significantly lower resolutions of observations, errors in CESM outputs, and errors in WRF physics.

Comparisons of CESM/WRF- and ERA/WRF-simulated climatological temperature and precipitation at 10 km resolution show that CESM/WRF simulations agree very well with ERA/WRF and there is no precipitation discrepancy over high mountains along the west coasts of Sumatra and Java islands. The high-resolution climate simulation system CESM/WRF developed in this study can provide useful simulated climatological temperature and precipitation for Sumatra and nearby regions. The good agreement between CESM/WRF and ERA/WRF also gains the confidence of employing CESM/WRF for climate projections for Sumatra and nearby regions.

Data Availability

The WRF model, CESM outputs, observations, and reanalysis employed in this study are publicly available.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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