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Impacts of a warming marginal sea on torrential rainfall organized under the Asian summer monsoon

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Monsoonal airflow from the tropics triggers torrential rainfall over coastal regions of East Asia in summer, bringing flooding situations into areas of growing population and industries. However, impacts of rapid seasonal warming of the shallow East China Sea (ECS) and its pronounced future warming upon extreme summertime rainfall have not been explored. Here we show through cloud-resolving atmospheric model simulations that observational tendency for torrential rainfall events over western Japan to occur most frequently in July cannot be reproduced without the rapid seasonal warming of ECS. The simulations also suggest that the future ECS warming will increase precipitation substantially in such an extreme event as observed in mid-July 2012 and also the likelihood of such an event occurring in June. A need is thus urged for reducing uncertainties in future temperature projections over ECS and other marginal seas for better projections of extreme summertime rainfall in the surrounding areas.

Global climate model projections for the 5th Assessment Reports (AR5) of the Intergovernmental Panel for Climate Change (IPCC) indicate that the global hydrological cycle will intensify in future under the global warming[1], with increasing precipitation over wet climate regions at present, especially in the tropics and summertime subtropical/midlatitude Asia[2], a region of growing economy and population. In these regions summertime precipitation is produced mostly by meso-scale convective systems, which occasionally yield extremely heavy rainfall locally causing serious flooding and/or landslides with casualties. Owing to their smallness, however, convective systems are not represented explicitly in any of the current IPCC global climate models. To assess future occurrence of convective precipitation extremes, one currently needs to rely on effective use of a cloud-resolving regional model into which future changes in large-scale atmospheric state projected by global climate models are somehow incorporated, for example, through the "pseudo–global warming (PGW)" approach[3–6].

Extreme rainfall events occur under convectively-unstable stratification, which requires warm, moist air near the surface. Through the nonlinear Clausius-Clapeyron relationship between saturated vapor pressure and temperature, amount of near-surface moisture available for convective rainfall is highly sensitive to sea-surface temperature (SST) over the warm ocean[7]. During the last century, ECS has undergone persistent warming that is greater than the averaged warming over the global ocean[8], and the climate model projections suggest that the pronounced warming is likely to continue into future[9]. Resolutions of the current IPCC models are, however, insufficient for reproducing fine SST distributions along the warm western boundary currents and continental marginal seas, including the Kuroshio and ECS, respectively.

The IPCC climate models project a future increase in summertime precipitation over East Asia[2], including Japan, where the Asian summer monsoon brings the wettest season in June and July (Fig. 1). Heavy convective rainfall often occurs when near-surface monsoonal southwesterlies carry moist air from the tropical oceans toward a quasi-stationary seasonal rain front called "Baiu (Meiyu)" front[6,10], extending from subtropical China to Japan (Fig. 1a). The moist airflow is most likely to affect the western portion of Kyushu, the westernmost main island of Japan facing ECS. Due to its bathymetric effect[11], the shallow ECS is cooled off strongly by

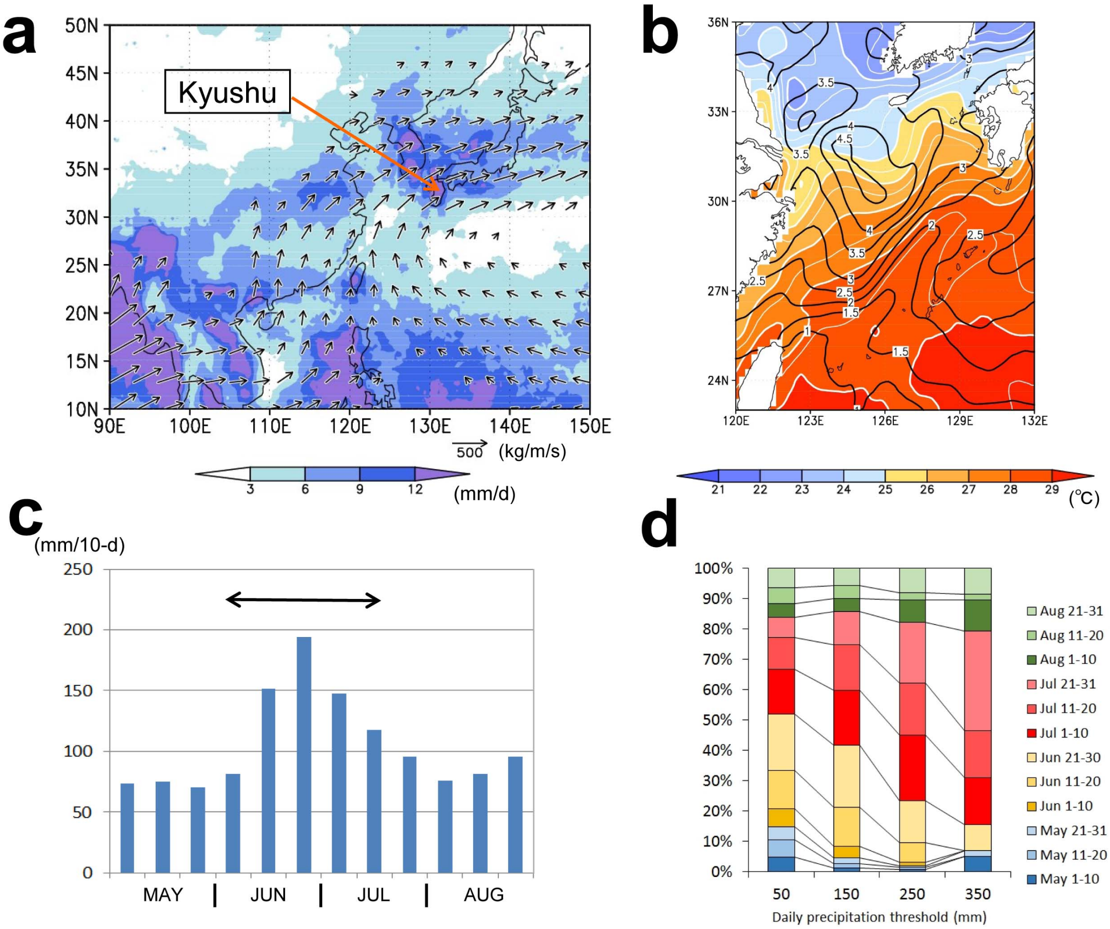

Figure 1 | Climatologies of the Baiu/Meiyu rain front and rain events in Kyushu Island. (a), July climatologies of monthly precipitation (mm d^{-1}; color) and vertically-integrated moisture flux (kg m^{-1} s^{-1}; vectors). (b), Monthly SST climatology (°C; color) for July, and climatological SST rising from June into July (°C; black lines). (c), Climatological bi-pentad precipitation (mm) over western Kyushu. The arrow indicates the climatological Baiu period. (d), Seasonality in frequency of precipitation events that occurred in western Kyushu and its dependency on daily precipitation threshold for selecting rain events as given on the lower abscissa. Total accumulated numbers of the selected events based on the individual thresholds are given on the upper abscissa. Data sources for this figure are given in Supplementary Information S1. The Grid Analysis and Display System was used for creating the maps in (a) and (b).

monsoonal northerlies in winter and then warms up into August. As part of this large seasonal march in SST, ECS exhibits 2–4°C warming from June into July (Fig. 1b; Supplementary Fig. S1), to which the shallow bathymetry of ECS[11] and warm-water advection by the Kuroshio[12] contribute.

Although the vital importance of lower-tropospheric water vapor transport for torrential rainfall events has been confirmed, impacts of SST on those events have not been quantified yet. Detailed analysis of daily precipitation observed at manned and automated (AMeDAS) weather stations over western Kyushu reveals that extreme rain events (exceeding 250 mm a day) occur mostly in July (Fig. 1d). When a larger number of modest precipitation events are included, however, the peak period is shifted into late June, the core period of the Baiu rainy season (Fig. 1d), as in the rainfall climatology (Fig. 1c). This is suggestive of the potential contribution from seasonal SST rise over ECS from late June to late July toward heavy rainfall over Kyushu.

In fact, the SST-precipitation relationship is well recognized in the tropics. A recent study[13] reports that a tendency for precipitation in the tropical Indian Ocean and Western Pacific to increase linearly at ~2 mm day^{-1} with an increase of 1°C in local SST holds up to extremely high SST (31°C) above an upper threshold (28–29.5°C) that has been supposed to exist. This is an indication that the impact of SST on tropical precipitation is more important than what was previously thought. In mid-latitudes, however, importance of SST for precipitation is still debatable, due partly to the weakness of precipitation signals that could be forced by relatively low SST.

An outstanding issue is thus whether the rapid seasonal SST rising in ECS can exert any significant influence on the occurrence of monsoonal heavy rainfall events over Kyushu at present and in future. This issue is addressed through a set of numerical simulations with a cloud-resolving regional atmospheric model[15], with primary focus on a torrential rainfall event that occurred on the 11th through 14th of July 2012 as a typical test case (see Methods). In that event, a number of weather stations over Kyushu observed rainfall with hourly rate exceeding 25 mm over many hours and 24-hour totals exceeding 100 mm, with records set at eight stations. Consequently, a severe flooding situation caused more than 20 casualties.

Results

The model performance is assessed in our control simulation (CTRL), in which high-resolution SST over ECS for mid-July 2012 was prescribed as the model lower-boundary condition. CTRL is found to reproduce the observed precipitation successfully (Fig. 2), with respect to locations and magnitudes of its local maxima. A backward-trajectory analysis reveals that air parcels transported into the areas of heavy precipitation over Kyushu traveled over south-western ECS (Supplementary Fig. S2). The low-level monsoonal southwesterlies, as observed typically south of the Baiu/Meiyu rain front[10] (Fig. 1), carried those air parcels, to which the warm Kuroshio over ECS supplied moisture to maintain convectively unstable stratification[14] (Supplementary Fig. S2).

The importance of the seasonal ECS warming is assessed through a seasonal-march (SMCH) experiment, in which each of the climatological-mean bi-pentad SST fields observed from June to August is prescribed on the model lower boundary while the large-scale atmospheric condition was kept the same as in CTRL for the mid-July event. The experiment indicates an unambiguous tendency for precipitation over Kyushu to increase with SST over ECS, especially with SST for the mid-July and later periods (Fig. 3), which is consistent with the most frequent occurrence of heavy rainfall events in late July (Fig. 1). Another SMCH experiment that is conducted with the atmospheric condition observed in another event on June 19th, 2001 also exhibits qualitatively the same sensitivity of precipitation over Kyushu to SST over ECS (Supplementary Information S2 and Fig. S5). Compared with CTRL, total precipitation simulated in SMCH for the July 2012 event would increase by 20% if it had occurred in late July (S12Jul31), since the ECS warming renders the near-surface stratification further unstable for convective precipitation systems to develop (Supplementary Fig. S3). Unlike in these SMCH experiments, the rain gauge data indicate that heavy precipitation events occur much less frequently in August than in July (Fig. 1d). This is because the Baiu/Meiyu rain front and associated upper-level westerly jetstream, which organize large-scale ascent, move northward in weakening by August[16].

Potential influence of future ECS warming is assessed in what may be called "future climate simulation (FC)". This is as an extension of the SMCH experiments but with area-averaged future increments in air temperature and SST taken from the IPCC CMIP5 projections[17], which have been added to the atmospheric state observed in the mid-July event and the climatological OISST data, respectively (see Methods). The projected warming of ECS and the overlying atmosphere leads to significant increases in precipitation simulated over Kyushu (Fig. 4). With the atmospheric and SST increments derived from their multi-model ensemble means (MMEs), the fractional rainfall increase in July is 30% in the 2040s (Jul40MME) and 45% for the 2090s (Jul90MME) relative to the present climate simulation (JulPC). For crudely evaluating uncertainties in the simulated precipitation increase introduced by those in the projected SST increment, the FC simulations were repeated by replacing the MMEs of projected increments of SST fields with the projected minimum (min.) or maximum (max.) increment of SST in ECS, and the vertical profiles of incremental air temperature obtained by the MMEs were also replaced with those obtained by the corresponding models. The differences in the simulated precipitation arising from these three types of increments are found to be rather small (Fig. 4), confirming the robustness of the enhanced rainfall over Kyushu into future. The dominant contribution from the future SST increase over that from the atmospheric warming has been revealed in a comparison between two additional sets of the FC experiments, one with the SST increment only (e.g., JulMME90(S)) and the other with the atmospheric warming only (e.g., JulMME90(A)). The atmospheric warming augments moisture availability for convective precipitation, but near-surface stratification would be stabilized without the SST warming (Supplementary Fig. S6). Although none of the low-level monsoonal southwesterlies, mid-tropospheric westerlies and vertically integrated water vapor flux over ECS into Kyushu significantly changes into future, enhanced surface evaporation due to higher SST renders near-surface atmospheric stratification over ECS more convectively unstable (Supplementary Figs. S6–S9).

The same experiments are repeated but with SST projected for June (Jun40 and Jun90). Though less sensitive to the SST increment than for July, rainfall over Kyushu simulated by a particular FC experiment with June SST to which the maximum increment among the CMIP5 models for the 2040s has been added (Jun40max) is comparable to that in CTRL. The potential is thus suggested that such a torrential rain event as observed in mid-July 2012 can occur over Kyushu as early as in June under the warmed future climate. Note that the SST sensitivity of the Kyushu rainfall shown in Fig. 4 does not necessarily seem consistent among the simulations, because in some cases a substantial fraction of the enhanced convective precipitation is simulated over ECS rather than over Kyushu.

Highlighting the distinct seasonal march of SST over ECS as one of the critical factors in controlling the seasonality of the occurrence of

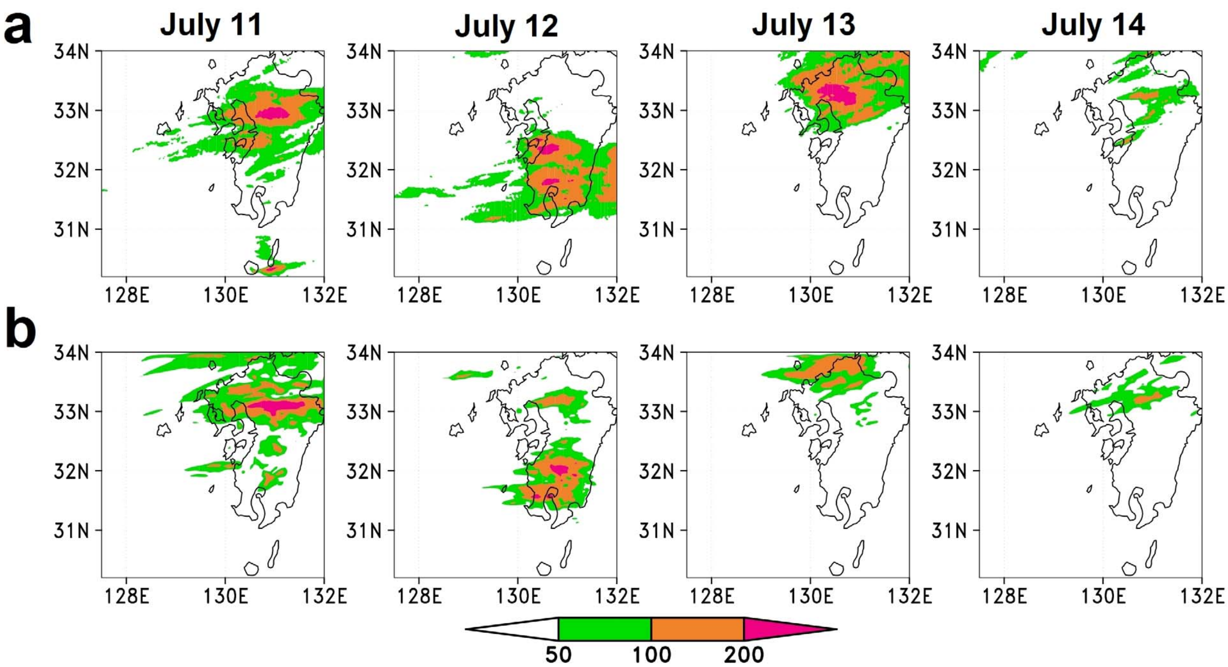

Figure 2 | Maps of daily precipitation (mm) during the torrential rain event in mid-July 2012. (a), Based on JMA radar observations. (b), In the control simulation (CTRL). The Grid Analysis and Display System was used for creating the maps in this figure.

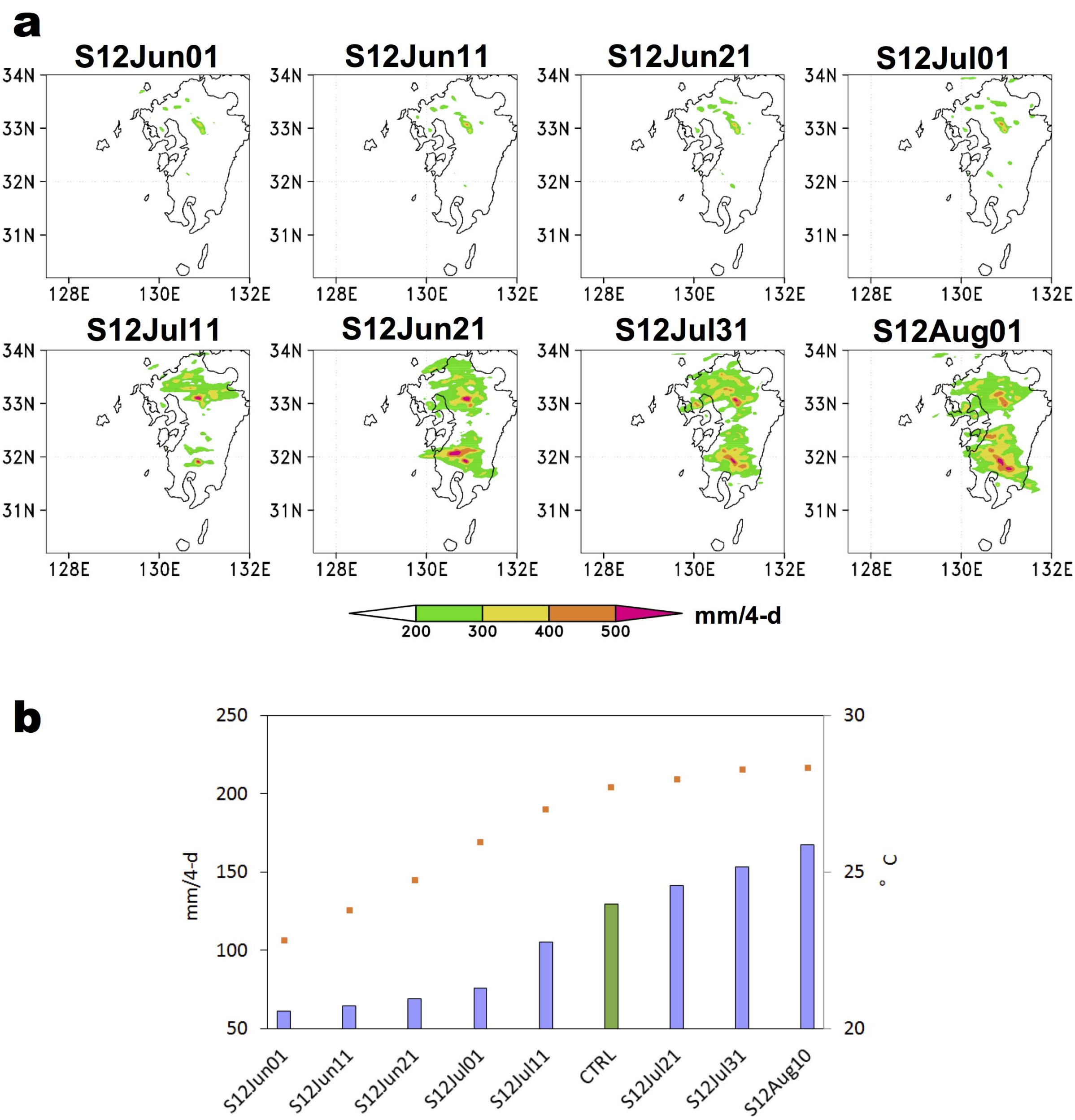

Figure 3 | Impacts of seasonal ECS warming on rainfall over Kyushu. (a), Maps of 4-day precipitation (mm) obtained in the seasonal march simulations (SMCH), in each of which climatological bi-pentad OISST from June 1 to August 10, as indicated, is assigned while the atmospheric conditions are kept the same as in CTRL. (b), (bar) 4-day precipitation (mm; left axis) averaged over Kyushu [31.0°N–34.1°N, 129.5°E–131.8°E] in the SMCH runs, and (square) SST (°C; right axis) averaged over the southern ECS [27°N–31°N, 123°E–128°E] assigned. The Grid Analysis and Display System was used for creating the maps in this figure.

torrential rainfall events over Kyushu during the Baiu season, the present study has shown a possibility of the future ECS warming to enhance precipitation in a torrential rainfall event and thereby modulate the earlier occurrence of such an event. However, future changes in the atmospheric circulation can also exert some impacts on torrential rain events. The latest GCM projections indicate future intensification of the East Asian summer monsoon[1], with augmented the northeastward moisture flux from the tropics into the Baiu/Meiyu frontal zone. Furthermore, its projected southward shift[6,18] will lead to the future delay in the termination of the Baiu period. These changes may become another factors for future increase in precipitation along the Baiu rainband. Though beyond the scope of the present study, the combined influence of the changes in the atmospheric circulation and the ECS warming on the future occurrence of torrential rainfall events should be investigated in future.

In summary, the present numerical study has revealed the distinct seasonal warming of ECS as an important factor in causing a particular torrential rain event in Kyushu that occurred in mid-July 2012, which is found to explain the particular seasonality of torrential rain events observed in Kyushu under the East Asian summer monsoon. Although the importance of both the moisture flux convergence and moisture availability over the adjacent oceans has been recognized for heavy rainfall events[18], the role of SST has not been elucidated yet. Our study suggests that the pronounced future warming of ECS has the potential to increase rainfall significantly (30–45%) in such an event as observed in mid-July 2012 over Kyushu, enhancing the future risk of flooding and landslides in July and even in June. A recent cloud-resolving model simulation projects substantial increases of total rainfall and heavy rainfall during the Baiu season[6]. We show that the rapid ECS warming into future can aug-

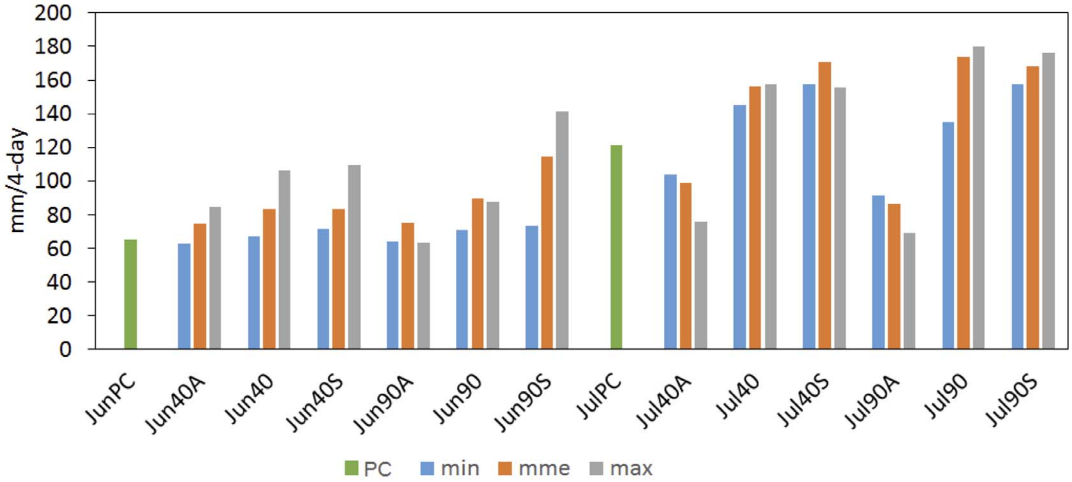

Figure 4 | **Impact of projected future ECS warming on rainfall over Kyushu.** 4-day precipitation (mm) averaged over Kyushu [31.0°N–34.1°N, 129.5°E–131.8°E] obtained by the future climate simulations (FC). Each of them is labeled "MmmPPSSS(A)", where "Mmm" refers to a month, "PP" to a decade of interest (i.e., "40" for the 2040s and "90" for the 2090s), "SSS" to kind of statistic (i.e., "min", "max" and "MME" denoting minimum, maximum, and multi-model ensemble mean, respectively), and the suffix "(S)" and "(A)" to a subset of the simulations where only SST and the vertical profile of air temperature, respectively, is modified over ECS. These FC simulations are compared with the "present climate (PC)" runs that have been conducted with the climatological SST observed in June and July, referred to as "JunPC" and "JulPC", respectively.

ment the likelihood of torrential rainfall events not only in July but also in June, suggesting the increasing risk of earlier occurrence of summertime flooding in future. Although our simulations target on the Kyushu Island of Japan, the results obtained here are relevant for other subtropical/midlatitude coastal areas where convective rainfall can occur in summer with moist airflow from the surrounding oceans, including the continental marginal seas for East Asia, the Gulf of Mexico and the subtropical Atlantic for the United States[19], and the Mediterranean for southern Europe[20]. Although the future precipitation increase in our regional-model simulations is robust qualitatively, the amount of the increase is rather sensitive to the SST increment projected in the CMIP5 models, which shows large quantitative uncertainties[9]. The present study urges the need for reducing uncertainties in the SST projection over the marginal seas and along the warm western boundary currents, for better future projection of summertime precipitation in the surrounding coastal regions and islands, especially where they are facing a steady rise of the sea surface, which is useful for planning out disaster prevention and water management over these regions into future.

Methods

Model set-up. The simulations in the present study utilize the WRF model[15] version 3.4.1, with 30 vertical levels up to the 50-hPa level. To resolve individual convective cloud systems explicitly over Kyushu and the maritime domain to its immediate upstream, horizontal grid spacing is set as high as 3 km within the model inner domain (Supplementary Fig. S4). This domain is nested within the intermediate and outer domains, where horizontal grid spacing is 9 and 27 km, respectively, and the Kain-Fritsch convective parameterization scheme[21] is adopted for implicitly representing convective rainfall. No such scheme was used for the inner domain. Each of the domains employs Yonsei University planetary boundary layer scheme[22], MM5 similarity surface model[15]. the WRF single-moment 3-class microphysics scheme[23]. Other sophisticated microphysics schemes[24,25] are also tested, but they rather tend to overestimate precipitation, similar to a recent sensitivity study[25]. Atmospheric data used for the initial condition and lateral boundary condition for the outer domain for each of our 120-hour model integrations are based on the Global Forecast System (GFS) Final Analyses[26] with horizontal resolution of 1° × 1°. For each of the nested domains, one-way nesting is used and the lateral boundary conditions are supplied from the parent domain.

Control and seasonal march simulations. High-resolution (1/12°) daily SST fields for mid-July 2012 produced by the Japan Coastal Ocean Predictability Experiment (JCOPE) reanalysis system[27] are used for the model lower-boundary condition of the control simulations (CTRL). The seasonal-march simulations (SMCH) utilize the daily SST climatology for the period 1985–2004 with 1/4° resolution based on the OISST[28], in which both satellite measurements and in-situ observations are incorporated. The SMCH runs are designated as "S12MonDD", where "S" refers to "SMCH", "Mon" to month (Jun, Jul or Aug), and "DD" to day (e.g., 01). The simulations were initialized at 0000 UTC on 10 July 2012, approximately 36 hours prior to the beginning of the rainfall event, so as to reduce the influence of the spin-up. Almost the same results are obtained when the initial time is shifted by six hours earlier or later (Supplementary Fig. S10). For each of the SMCH runs, all the initial meteorological parameters were kept the same as for CTRL, and the only change introduced was the SST data as mentioned above.

Future climate simulations. For assessing the impact of future ECS warming on precipitation, another set of simulations ("Future Climate" or FC) was conducted where large-scale future changes in SST and/or vertical air-temperature profiles projected in the CMIP5 (Phase 5 of Coupled Model Intercomparison Project) global climate models[15] were incorporated into the high-resolution climatological OISST SST and the atmospheric conditions observed during the rainfall event, respectively. This experimental design, which is similar to the PGW approach[3–6], is advantageous, since horizontal resolutions of the CMIP5 climate models are lower than those of the OISST and GFS final analysis (See Supplementary Information S3 for the details of the CMIP5 SST data). Although exactly the same synoptic-scale weather patterns as observed in 2012 would never occur in future, similar patterns should occur in the Baiu/Meiyu season.

For a subset of the FC simulations, the projected thermodynamic changes due to increasing anthropogenic greenhouse gases under the RCP4.5 scenario[17] were taken from 32 CMIP5 climate models. Specifically, monthly fields were averaged separately for June and July over the climate models in which temperature data were available at all the standard pressure levels. These monthly model-ensemble fields were averaged within the inner domain of the WRF model before computing decadal means for the 1990s, 2040s and 2090s. The changes in the vertical temperature profile thus obtained from the 1990s into both the 2040s and 2090s were then added to the original GFS analyses uniformly within the entire model domain during the 5-day period for the WRF model integration (11 through 15, July 2012). The horizontal averaging is necessary to prevent any large-scale wind changes from being added into the initial condition for the FC through thermal wind balance. As in previous modeling studies[29–31], the same relative humidity (RH) field as used for CTRL was assigned as the initial and boundary conditions for all the FC simulations, since studies of the global atmospheric moisture have found little long-term change in RH associated with the recent warming trend[30,32,33]. These procedures are to mimic thermodynamic conditions around the 2040s and 2090s under the global warming.

The PGW approach for projecting the future changes in precipitation has been tested by some hindcast experiment[34] and becoming widely utilized[3,4,35]. The main advantage of this approach is a reduction of the model bias yielded in global climate model (GCM) projections. The large model biases in the GCM future projections may contaminate the results of the downscaling modeling results. The lateral boundary and initial conditions for the PGW approach consist of atmospheric reanalysis data under the present-day climate and the components of climatic changes projected by the GCMs. Although this GCM-projected component can yield some uncertainty into the simulated results based on the PGW approach, the usage of the reanalysis data can greatly reduce the overall uncertainty without introducing any biases of the GCMs in their reproduction of the current climatic conditions. Meanwhile, the main shortcoming of the PGW approach lies in its inability to include the influence of future modulations in the inter-annual variability and future changes in large-scale disturbances, including the future changes in the position of the Baiu front, which must be assumed to be unchanged. Quantitative assessment of this uncertainty is beyond the scope of this study and should be performed in future study.

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Author contributions

All authors designed the numerical experiments and data analysis after conceived by H.N. A.M., T.M., S.I. and M.Y. conducted the numerical simulations. K.N. and T.M. pre-processed the CMIP5 data. N.A. analyzed rain-gauge data. A.M., H.N. and Q.M. wrote the initial draft of the paper, to which all authors contributed edits throughout.

Additional information

Supplementary information accompanies this paper at http://www.nature.com/scientificreports

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