Added value of high-resolution climate projections over South Korea on the scaling of precipitation with temperature

Liying Qiu$^{1,*}$ and Eun-Soon Im$^{1,2,*}$

$^1$ Department of Civil and Environmental Engineering, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, People's Republic of China

$^2$ Division of Environment and Sustainability, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, People's Republic of China

$^*$ Authors to whom any correspondence should be addressed.

E-mail: ceim@ust.hk and liying.qiu@connect.ust.hk

Keywords: precipitation-temperature scaling, added value of dynamical downscaling, pseudo global warming, RCP8.5 scenario

Supplementary material for this article is available online

Abstract

This study evaluates the resolution dependency of scaling precipitation with temperature from the perspective of the added value of high-resolution (5 km) dynamical downscaling using various kinds of long-term climate change projections over South Korea. Three Coupled Model Intercomparison Project Phase 5 (global climate models (GCMs) with different climate sensitivities, and one pseudo global warming (PGW) experiment, are downscaled by Weather Research and Forecasting one-way double nested modeling system with convective parameterization for the reference (1976–2005) and future (2071–2100) periods under RCP8.5 scenario. A detailed comparison of the driving GCM/PGW, 20 km mother simulation, and 5 km nested simulation demonstrates improved representation of precipitation with increasing resolution not only in the spatial pattern and magnitude for both the mean and the extremes, but also in a more realistic representation of extreme precipitation's sensitivities to temperature. According to the projected precipitation changes downscaled from both GCM ensemble and PGW, there will be intensified precipitation, particularly for the extremes, over South Korea under the warming, which is primarily contributed by convective precipitation increase that shows higher temperature sensitivity. This study also compares the extreme precipitation-temperature scaling relations within-epoch (apparent scaling) and between-epoch (climate scaling). It confirms that the magnitude and spatial pattern of the two scaling rates can be quite different, and the precipitation change over Korea under global warming is mainly controlled by thermodynamic factors.

1. Introduction

The added value of high-resolution regional climate models (RCMs) has been increasingly recognized for climate change studies, particularly across regions with complex stationary features (e.g. topography, land-sea contrast) and/or those affected by small-scale physical processes, as well as for reducing the scale mismatch between various impact assessment models and their climate inputs (Di Luca et al 2015). Using powerful computing architectures, attempts have been made over the past several years to increase the spatial resolution toward a few kilometers scale, demonstrating some improvements brought by higher-resolution modeling. However, the grid spacing of existing long-term climate simulations mostly remains in the range of 10–50 km (e.g. CORDEX, Giorgi and Gutowski 2015; EURO-CORDEX program, Jacob et al 2020; CORDEX-CORE, Giorgi et al 2021). To obtain momentum for supporting the higher-resolution simulation despite the massive computational burden, there is a need to provide an objective and unambiguous assessment of its positive effects. Although the added value of RCMs at the typical grid size ($\gtrsim$10 km) against the driving global climate models (GCMs) has been well documented based on comparisons against the best available observational data (e.g. Torma et al 2015,
Ciarello et al. (2021), elaborate attributes of higher-resolution simulations are unlikely to be validated in their entirety unless observations are made in comparable resolutions. Moreover, proving the potential physical realism of a high-resolution simulation for the future change signal in response to emission forcing is far more onerous. There is no substantial 'answer' for the assessment when it comes to climate change and our understanding of relevant physical processes is still of high uncertainty (Lenderink et al. 2019). Against this backdrop, it is unsurprising that only a few studies (e.g. Giorgi et al. 2016) have expounded on the benefit of increasing resolution from the standpoint of future climate change.

The Korean Peninsula, whose climate features are strongly dependent on the sharp topographical gradient and land-sea interaction (Im et al. 2006, Qiu et al. 2020), can serve as a good testbed for assessing the applicability and necessity of high resolution in climate change studies. Significant uncertainty prevails in the future projections of precipitation over this region, particularly for the summer precipitation that is relevant to various mechanisms and shows high inter-annual variability (Ahn and Kim 2019). These include large-scale precipitation (LP)—generally related to the East Asia summer monsoon (EASM)—and convective precipitation (CP) induced by the local convective instability (Hong and Ahn 2015). So far, 12.5 km adopted by five RCMs for downsampling HadGEM2-AO (Ahn et al. 2016, Hong and Ahn 2015, Im et al. 2017, Oh and Suh 2018) remains the finest resolution in RCM ensemble for long-term climate change projections focusing on Korea. This RCM ensemble projection would be named HadGEM2-AO/12.5km in this study for comparison with our result. The HadGEM2-AO/12.5km indicated that there is likely to be increased summer precipitation in Korea as future emission forcing becomes stronger, which is in line with the HadGEM2-AO projection. Although the HadGEM2-AO/12.5km could establish the regionally diverse magnitude and statistical significance of precipitation change, the general pattern of the change direction appears to be strongly constrained by the single driving forcing that may inadvertently lead to a biased conclusion. Therefore, for a more comprehensive assessment, it is important to conduct high-resolution simulations driven by multiple GCMs covering a diverse range of climate sensitivities to the anthropogenic forcing over this region.

Aside from the limited number of high-resolution runs, the lack of investigation in the precipitation change processes stymies the understanding of how the regional and local climate will evolve (Im et al. 2017, Oh and Suh 2018). Based on a comparison between the 5 km and 20 km grid spacing for downscaling in a perfect boundary condition experiment over South Korea, Qiu et al. (2020) showed an improved partitioning between CP and LP as two components of the total precipitation (TP), and a more plausible precipitation-temperature relationship that is aligned with observation, can indeed be realized in the higher resolution, benefiting the overall precipitation representation. In turn, this denotes a great potential for the higher resolution to create a more reliable precipitation projection under global warming given the expected difference in the responses of CP and LP to the warming (Berg et al. 2013, Park and Min 2017).

Typically, precipitation intensity, particularly for high and extreme events, is largely impacted by the thermodynamic law, which states that the saturation vapor pressure will increase as it warms (Giorgi et al. 2016). This governs both the day-to-day precipitation-temperature relationship (apparent scaling, AS; Ali et al. 2018, Bui et al. 2019) and the precipitation change induced by climatic temperature warming (climate scaling, CS; Chou et al. 2012, Giorgi et al. 2019). These two different 'scalings' follow the definition mentioned in Fowler et al. (2021): (a) AS refers to the intra-annual temperature scaling of extreme precipitation within each epoch, and (b) CS is the relationship of the change in extreme precipitation and mean temperature between the reference and future periods. While there is a theoretical scaling rate of 6–7%/°C for the saturation vapor pressure (Clausius–Clapeyron (CC) scaling), the scaling behaviors at the local level can vary significantly with dynamic factors and the type of precipitation considered (Berg et al. 2013, Borodina et al. 2017). Also, the AS in the present-day climate was previously supposed as an important indicator for the CS (e.g. Lenderink and van Meijgaard 2008), but several recent studies suggest that the magnitude and spatial pattern of these two scaling rates can be quite different (Bao et al. 2017, Wang et al. 2017, Zhang et al. 2017, Sun et al. 2020).

Nevertheless, it is notable that previous findings are based on either GCM or coarse-resolution RCM (>50 km), and that they only focused on the scaling relations of TP. Thus, a higher-resolution RCM ensemble with a more reliable representation of the precipitation characteristics is necessitated for further investigation (Sun et al. 2020). With the aid of a comprehensive downscaling practice, it is important to explore how the proved added value of the higher resolution in better representing CP-LP components (Qiu et al. 2020) would affect the regional precipitation projections, both with respect to their individual contributions and the resulting change pattern of precipitation. To the best of our knowledge, no analysis focusing on quantifying the precipitation-temperature relations of both AS and CS and the resultant precipitation change behavior has ever been conducted, although the impact of horizontal resolution on various aspects of climate simulation has been previously explored.
As a follow-up study of Qiu et al (2020), this study explores the application and added value of the 5 km high-resolution in parameterized-convection RCM for projecting regional precipitation change, taking the Korean Peninsula as an example. The 5 km high-resolution RCM is used to downscale three GCMs with different climate sensitivities and the reanalysis data imposed by an idealized pseudo global warming (PGW) forcing. While the adoption of multiple GCMs facilitates the consideration of a certain range of climate sensitivity and uncertainty in the projected boundary conditions, a rather idealized and well-constrained setting in the PGW experiment, which excludes systematic errors in GCMs, is also included (Lenderink et al 2021). Such an experimental design enhances the robustness of precipitation projections and allows for a more comprehensive understanding. In particular, incorporating the PGW experiment improves the understanding of the thermodynamic effect on the precipitation change and the scaling relations, thus improving the reliability of future change patterns.

To address the issue of added value for the high resolution, our analysis will focus on comparing precipitation reproduction and projection (section 3.1) and the scaling behaviors expounding on the relationship of changes in TP as well as LP and CP with temperature (section 3.2) across the different resolutions (i.e. 5 km nested-domain simulation versus 20 km mother-domain simulation versus driving GCMs/PGW).

2. Data and method

2.1. Model simulations

This study employs the latest release of the Advanced Research Weather Research and Forecasting (WRF) model (Skamarock et al 2019), version 4.2, to downscale three selected GCMs and one PGW experiment over South Korea. The mother domain is of 20 km resolution over northeastern Asia (hereinafter as WRF20), and the nested domain is of 5 km resolution focusing on the Korean Peninsula (hereinafter as WRF05) (figure S1 (available online at stacks.iop.org/ERL/16/124034/mmedia)). The domain configurations and physical parameterizations (table 1) follow those adopted in Qiu et al (2020), which have undergone a sensitivity test and demonstrated optimal performance over the target region. It is worth noting that 5 km is within the 'gray-zone resolution' (i.e. 4–10 km), wherein deep convection is partly resolved and partly sub-grid. As per the sensitivity test, convection-permitting simulations cannot be adequately conducted across 5 km over the selected region. Thus, the Kain-Fritsch scheme, in conjunction with a trigger function modulated by moisture-advection, is implemented as the cumulus scheme for both WRF20 and WRF05 here.

Three Coupled Model Intercomparison Project Phase 5 (CMIP5, Taylor et al 2012) GCM projections under the Representative Concentration Pathway (RCP) 8.5 scenario are designated for the lateral boundaries: CCSM4, NorESM, and HadGEM2. They have all gain recognition as ‘good’ CMIP5 models over the EASM region (Seo et al 2013) and cover a range of 3.4 °C–5.6 °C temperature increase for considering low, middle, and high climate sensitivities respectively. The simulations span two 30-year-plus-1-month time slices for the reference period (REF) and the future period (FUT). The first 13 months is a spin-up period that the analyses are solely based on the 29 year simulations. Table 1 lists detailed information on these simulations.

The PGW experiment is an idealized warming experiment that closely follows the approach adopted by Liu et al (2020) and Adachi and Tomita (2020). The boundary condition for the PGW experiment can be elucidated as follows:

\[ B_{\text{PGW}} = A + \langle GCM_{\text{FUT}} \rangle - \langle GCM_{\text{REF}} \rangle. \] (1)

Here, A denotes the reanalysis data from ERA-Interim (Dee et al 2011) during the reference period 1986–2005, and \( \langle GCM_{\text{FUT}} \rangle - \langle GCM_{\text{REF}} \rangle \) represent the ensemble-mean change signal under the RCP8.5 scenario. The angle bracket \( \langle \rangle \) indicates the multimodel mean of the three GCMs, and the superscripts \( \text{FUT} \) and \( \text{REF} \) signify an average over the integration time of FUT and REF. The perturbed physical fields include all the downscaling inputs (e.g. atmospheric temperature, horizontal wind, humidity, and surface pressure). The comparison between the direct downscaling and PGW experiments can largely reduce the systematic error in GCMs and imply the thermodynamic contribution toward the climate-change signal (Liu et al 2017, Lenderink et al 2019, Adachi and Tomita 2020). Notably, only a 20-year-plus-1-month experiment is performed for the PGW experiment to maintain consistency with the 20-year analysis plus 1-month spin-up downscaling of the ERA-Interim in Qiu et al (2020).

The corresponding outputs are named as Model_source-period. For example, CCSM4/WRF20-REF refers to the 20 km downscaling of CCSM4 for the REF period. The ensemble mean (ENS) stands for the unweighted multi-model mean of the three GCMs. It is noteworthy that we mark the downscaling of ERA-Interim during REF as PGW_source-REF.

2.2. Observation and data post-processing

This study uses the model output of daily mean 2-metre temperature and daily precipitation for the analysis. Specifically, the precipitation (TP) is represented as the sum of CP from the cumulus scheme and LP from the microphysics processes in the numerical
models (i.e. TP = CP + LP). For the purpose of validation, two kinds of daily observational datasets are used (Table 1): (a) the gridded observation of K-Hidra from Noh and Ahn (2021), and (b) the in-situ observation from 59 KMA stations (KMA-Sta). Here, the two datasets are not independent of each other: the gridded K-Hidra is developed from the observation records of 389 gauge stations over South Korea. The primary reason for using both types of observation is that the gridded data covers a complete period and area considered and allows interpolation for the comparison among different resolutions. On the other hand, the in-situ station data avoids the influence from smoothing, which is important to preserve the extremely high values and validating the high-resolution simulations. The model outputs are interpolated onto the 0.25° grid of K-Hidra, and extracted at the grid points closest to the station locations for the comparison against the two observation datasets, respectively. Meanwhile, to utilize the 5 km high-resolution simulation products in the best possible manner, the simulation output is presented on the 5 km grid for analyses that do not need to be validated against observation data. Additionally, we test the results of all the analyses (not shown) by interpolating the simulation output and observation onto different resolutions (i.e. the grid of WRF05, WRF20, K-Hidra, and 150 km) to ensure that the uncertainty created by interpolation will not cause a significant discrepancy in the analyses (figures S3 and S4 are displayed as examples). For both model simulations and observation, the precipitation amount of less than 1 mm d⁻¹ is converted to zero in order to reduce the common overestimation of ‘drizzle days’ in the models (Giorgi et al 2019).

2.3. Scaling rates estimation

The AS calculation is based on the assumption that it is possible to estimate the scaling of precipitation with temperature by fitting the exponential regression relationship of (Wasko and Sharma 2015):

\[ P_{T+\Delta T} = P_T(1 + \alpha)^{\Delta T}. \]  

(2)

Since equation (2) is an exponential regression, each term should be considered dimensionless. The \( \alpha \) can be seen as the value of the scaling rate (%/°C) to describe precipitation change with temperature change. Then, the transformation equation of equation (2) (Ali et al 2018, Magan et al 2020) can be used to calculate the value of AS rate of the 99th percentile daily precipitation (P99) on daily temperature (\( A_{S99} \), %/°C):

\[ A_{S99} = \frac{P_{T+\Delta T}}{P_T} \Delta T = 100 \times (e^{\alpha} - 1). \]  

(3)

There are two mainstream methods to obtain \( \alpha \) for the specific quantile of precipitation: binning scaling on temperature (e.g. Lenderink et al 2011, Park and Min 2017) and quantile regression (e.g. Wasko and Sharma 2014, Ali et al 2018). Even though the results from the two different methods have proved to be similar if the sample size is large enough (>100 000 samples) (Ali et al 2018), quantile regression may be more suitable for carrying out quantitative analysis in this study since the number of wet events (less

| Model     | Resolution | CCMSM4⁴ | NorESM⁵ | HadGEM2⁶ | PGW |
|-----------|------------|---------|---------|----------|-----|
| GCM       |            | 1.25° × 0.9° | 2.5° × 1.9° | 1.875° × 1.25° | 0.75° × 0.75° |
| REF⁴      | CMIP5 GCM Historical 1977–2005 |         |         |         | ERA-Interim Reanalysis 1986–2005 |
| FUT¹d     | CMIP5 GCM RCP8.5 2072–2100 |         |         |         | REF + Ensemble mean change of three GCMs |
| RCM       | Mean Temp. Change | 3.4 °C (Low) | 4.1 °C (Middle) | 5.6 °C (High) | 4.4 °C |
| WRF20     | 20 km × 20 km, approximately 113.1°–141.4° E, 29.7°–45.8° N |         |         |         |         |
| WRF05     | 5 km × 5 km, approximately 125.1°–130.8° E, 32.9°–39.0° N |         |         |         |         |
| Physics   | Microphysics: WSM3 | Longwave and shortwave radiation: RRTMG | Surface layer scheme: the Revised MM5 | Land Surface Model: Noah scheme | Planetary boundary layer: the Yonsei University scheme |
| Observation | K-Hidra⁷ | Gridded rainfall observation dataset, 0.25° × 0.25°, 1977–2005 | Gridded data 1977–2005 | Observation dataset from 59 stations (Location marked on figure S1) |                |
|           | KMA-Sta⁸ | In-situ observation dataset from 59 stations (Location marked on figure S1) |         |         |                |

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**Table 1.** Experiment set-up, model configuration, and observation data.

*CCMSM4: the Community Climate System Model version 4 (Gent et al 2011)
*NorESM4: NorESM1-M, the Norwegian Climate Center’s Earth System Model (Bentsen et al 2013)
*HadGEM2: HadGEM2-ES, the Hadley Centre Global Environmental Model version 2 Earth System Model (Collins et al 2011)
*Analysis period. The simulations additionally include a 13 months spin-up period.
*K-Hidra: K-Hidra version 2020 (Noh and Ahn 2021)
*KMA-Sta: Station data maintained by the Korean Meteorological Administration (accessible on [https://data.kma.go.kr](https://data.kma.go.kr))
than 100 wet events/year × 30 year = less than 3000 wet events) on each grid point is much less when compared with the required number (i.e., >100 000 samples) for bin scaling. Comparatively, quantile regression is unbiased with sample size (Wasko and Sharma 2014), which can be described from daily precipitation intensity (P) and daily temperature (T) as:

\[ \log(P) = \beta + \alpha T \] (4)

where \( \beta \) and \( \alpha \) denote the fitted parameters at the target quantile (99th percentile in this study).

Here, the quantile regression is used to obtain the quantitative estimation on each grid point to derive the spatial pattern of AS\(_{P99}\) rate. However, it is poignant to remember that the peak-like behavior in the precipitation-temperature scaling with negative slope at high temperatures over Korea (Park and Min 2017), which is also commonly seen in many other places, could result in an underestimated AS rate produced by the quantile regression (Pumo and Noto 2021). To visualize the peak-like shape of precipitation-temperature relations, the binning curve of P99 versus daily temperature is also shown in section 3.2 by binning the daily precipitation events on the basis of daily mean temperature and calculating the 99th percentile of each bin’s wet events. The specific method for deriving the binning curve follows Park and Min (2017).

For the CS rate (\%/°C), the scaling rate is computed following the method mentioned in Sun et al (2020):

\[ CS = \left\{ \exp \left( \left[ \ln P_{\text{FUT}} - \ln P_{\text{REF}} \right] \div \left( T_{\text{FUT}} - T_{\text{REF}} \right) \right) - 1 \right\} \times 100\%. \] (5)

Here, \( P_{\text{FUT}} \) and \( P_{\text{REF}} \) are the P99 precipitation, and \( T_{\text{FUT}} \) and \( T_{\text{REF}} \) signify the mean temperature for the two periods, respectively. While equation (5) is also the transformation equation of equation (2), this \( \alpha \) is simply estimated by the ratio of (log) precipitation change and temperature change between the two periods. CS is utilized for elucidating the change rate per degree warming of different precipitation indices in section 3.1; on the other hand, specific CS\(_{P99}\)—the scaling of the period-median of the annual P99 between FUT and REF—is used for the comparison with AS\(_{P99}\) in section 3.2. All the calculations are conducted on each grid according to Sun et al (2020).

For South Korea, more than 50% of the annual TP and most extreme cases associated with the mesoscale convective system are concentrated in the summer (June-July-August, JJA) (Kim et al 2018, Oh and Suh 2018), so the analysis for precipitation evaluation and projection (section 3.1) will focus on JJA over the South Korean land. Four typical precipitation indices (see table S1, the definitions generally follow Ge et al (2021)) are calculated based on daily TP. Since the indices are calculated from daily precipitation, there is no result for PGW\(_{\text{PGW-FUT}}\) which is an idealized boundary (\( B_{\text{PGW}} \)) constructed by climatological mean statistics. Meanwhile, a wider temperature range of 8 °C–36 °C from all-year-round (following the range for AS estimation in Park and Min (2017) and Qiu et al (2020)) but extending the upper limit due to future warming) is taken into consideration in the AS\(_{P99}\) and CS\(_{P99}\) estimation to explore robust scaling results for single grid points and undertake a more comprehensive temperature distribution (section 3.2).

3. Results

3.1. Added value in current precipitation simulation and the projected change

We begin our analysis with the performance in the reproduction of JJA precipitation during REF. Figure 1 illustrates the seasonal mean precipitation averaged over South Korea land for all the models and resolutions, clearly demonstrating the improvement in TP reproduction through the downscaling chain of GCM-WRF20-WRF05, and the WRF05 is the closest to the K-Hidra observation (the grey dashed line). GCMs not only obscure the spatial variation of higher precipitation observed along the southern coast and across the north of the country (figure S2), but also show a significant dry bias commonly found for the EASM Mei-yu-Changma-Baiu front in the CMIP5 large ensemble (Seo et al 2013) as well as in the HadGEM2-AO\(_{12.5km}\) downscaling products over South Korea (Oh and Suh 2018). The WRF20 and WRF05 significantly reduce such dry bias and provide spatial patterns much closer to the observation. As shown in figure S3, the intercomparison of the ENS\(_{\text{REF}}\) products and K-Hidra aggregated and disaggregated across four different resolutions indicates the seasonal mean precipitation pattern can be well captured by both WRF20 and WRF05 up to a resolution of 25 km. However, if upscaled to a GCM-like resolution (i.e., 150 km), even the observation pattern is distorted. On the other hand, the WRF05 at fine grid can provide more spatial details that reflect a strong topographical effect on precipitation, also underscoring the significance of the high resolution for a better orography representation.

Meanwhile, a non-negligible overestimation of TP can be found in CCSM4\(_{\text{WRF20-REF}}\) and NorESM\(_{\text{WRF20-REF}}\). The decomposition into CP and LP in figure 1 indicates that this may be primarily attributed to the too-actively triggered parametrized precipitation (i.e. CP) in the 20 km simulations, especially along the high-elevation area, which is also found in Jin et al (2016) for a 27 km simulation over Northeast Asia compared to 9 km simulation. The improvement in the summer seasonal mean precipitation is contributed by the enhanced performance in the entire precipitation distribution (figure S4). The downscaling is capable of bringing about a
shift toward the higher intensity and WRF05 demonstrates its advantage for producing a higher portion of the heavy precipitation (>100 mm d⁻¹). Notable, a heavier tail of extreme precipitation is found in WRF05 and the station-based KMA-Sta data. The 0.25° gridded K-Hidra observation reveals a slightly smaller portion of heavy precipitation, which may have been smoothed out by the spatial aggregation. The ability to capture extremely heavy precipitation events is one of the key advantages of high-resolution simulations.

Such characteristics are also reflected by the relative bias in the precipitation indices compared against K-Hidra and KMA-Sta (figure S5). That is, for the extreme indices, Rx5day (Maximum consecutive 5 day precipitation) and R99p (Daily precipitation of the 99th percentile), the high resolution of WRF05 produces closer statistics to the KMA-Sta while it displays a slight overestimation for these extremes compared with K-Hidra. Here, our intention is not to compare the quality of the two kinds of observation. Instead, we want to point out the non-negligible uncertainty existed in the observation, especially for the validation of 5 km high-resolution RCM that usually lacks observation datasets at a comparable resolution. Nevertheless, regardless of the kind of observation data used, it is evident that the downscaling reduces the dry bias in GCMs. The eventual precipitation pattern in ENSWRF05-REF shows a qualitative and quantitative performance comparable to the perfect-boundary PGW WRF05-REF, although a slight overestimation against the observation is retained.

For the precipitation projection (figure 2), the ENSGCM shows an increase with the warming for either the mean or the extreme precipitation agreed upon by all three GCMs (the non-dashed area). Here, since the warming levels are different among the models, we use CS to describe the precipitation change per degree warming, but it is also pertinent to remind that warming can affect the change signal and rate as well. Figure S6 illustrates the CS in individual climate simulations for the JJA mean TP. For the model with stronger warming (e.g. HadGEM2 shows the highest temperature increase in this study), the projected precipitation shows a tendency toward higher CS with a more extensive increase signal across the domain. Similarly, the HadGEM2-AO12.5km projections also reveal varying precipitation change signals and magnitudes under the four different RCP scenarios (Oh and Suh 2018).

A larger ensemble spread in the downscaling products may be attributed to the higher natural variability in RCM, yet the model disagreement appears only in a limited area over the western part of the country and WRF05 shows a higher model agreement than WRF20. In general, the ensemble mean change of the three models ENSWRF05 is qualitatively consistent with the change in PGW WRF05-REF that JJA TP will increase in the future and the extremes will increase more prominently at around the CC rate. A more significant increase and model agreement are found across the southeastern coastal region, similar to HadGEM2-AO12.5km (Kim et al 2018, Oh and Suh 2018). In addition, the area with mixed change signals in ENSWRF05 is also of a relatively weak change in PGW WRF05.

Here, PGW projection can serve as a ’reference’ for the direct downscaling products of ENS by largely avoiding the systematic errors inherited from GCMs, since it is constructed with the ‘perfect boundary’. Although the intensification of TP over South Korea has been previously reported (e.g. Im et al 2017), this study reveals that the inter-model uncertainty and spread may still exist, particularly under different levels of warming and across different sub-regions. More importantly, the improved performance of precipitation reproduction during REF in WRF05 leaves a solid foundation to exemplify its reliability for future projections.
To investigate how the CP and LP affect the JJA precipitation change respectively, figure 3 illustrates the relative change of JJA mean TP between FUT and REF averaged over the land of South Korea as contributed by each component (e.g. \( \frac{\text{FUT CP} - \text{REF CP}}{\text{REF CP}} \times 100\% \)). Evidently, the TP increase is larger in the model with stronger warming, and the increase in CP makes a greater contribution than LP for all the models in all resolutions. However, as mentioned before, WRF05\(_{\text{REF}}\) shows a higher fraction of LP than WRF20\(_{\text{REF}}\). For the precipitation change, LP in WRF05 also contributes more to the total increase when compared with WRF20 or even reverses the LP change signal from a decline to an increase. For all the models considered, LP shows higher sensitivity to warming in the WRF05 (the value marked on the blue bar); however, the LP decrease still comprises a large area of South Korea in CCSM4\(_{\text{WRF05}}\) and NorESM\(_{\text{WRF05}}\), while HadGEM2\(_{\text{WRF05}}\) turns the decrease into an increase across the entire nation (figure S7). The CP change, on the other hand, retains its spatial pattern in the GCM-WRF20-WRF05 downscaling chain for all the models, but the decrease signal appears in CCSM4\(_{\text{WRF20/WRF05}}\) over the southwestern area (figure S8) which is also projected as CP decline in HadGEM2-AO 12.5km for the low-level warming (Oh and Suh 2018). Although with an inter-model spread that might be highly subject to the different levels of warming, the ENS\(_{\text{WRF05}}\) exhibits considerably high similarity with PGW\(_{\text{WRF05}}\).
Figure 4. (1) Apparent scaling rate of P99 ($\text{AS}_{\text{P99}}$, calculated via quantile regression) for TP in REF; (2) $\text{AS}_{\text{P99}}$ for TP in FUT; and (3) CS rate of the period median of annual P99 ($\text{CS}_{\text{P99}}$, normalized by grid-point temperature change) between FUT and REF from (a) ENS and (b) PGW. The last sub-figure is $\text{AS}_{\text{P99}}$ from K-Hidra. All the data have been first interpolated onto the 5 km grid. The value at the top right of each sub-figure is the spatial-average value over South Korea land. The unit is $\%/^{\circ}\text{C}$. The warm colors indicate equal to or greater than the CC rate.

not only for the TP mean change pattern, but also for CP and LP components.

Overall, despite a higher fraction of LP in the 5 km resolution, our results still support the previous finding that the CP is the main contributor to the TP increase over South Korea. Additionally, the projected sensitivity of CP to temperature warming is even higher when there is an increase in the resolution of climate simulations. But for LP, which has been proved to show no consistency in the projected pattern among different models and scenarios across this region (Kim et al 2018), the 5 km high-resolution downscaling may suggest that it is also expected to increase in the future warming.

3.2. Added value in the precipitation-temperature relationship in the extremes

Section 3.1 described the added value of the high-resolution dynamical downscaling in reducing the biases in precipitation simulations. This section will focus on investigating the precipitation-temperature variation behavior across different resolutions. Since such behavior is more robust for the extreme precipitation, which is projected by ENS$_{\text{WRF05}}$ and PGW$_{\text{WRF05}}$ to increase at CC rate under the RCP8.5 scenario, the scaling analysis will be conducted specifically for P99. Figure 4 shows the spatial patterns of $\text{AS}_{\text{P99}}$ for both REF and FUT and $\text{CS}_{\text{P99}}$ between the two periods for TP, calculated from quantile regression (equations (3) and (4)) at each grid point. The warm color in the map indicates a scaling rate equal to or higher than the CC rate. Figure 5 visualizes the binning curves of the 99th percentile daily precipitation along with temperature averaged over the 59 KMA stations for REF (green line) and FUT (red line), in comparison to the black line representing the binning curve derived from the KMA-Sta observation. The colored shading marks the standard deviation among the stations. The blue line represents the theoretical ‘adjusted REF’ line that we shift the green line of REF along the CC scaling rate of 7$\%$/^{\circ}\text{C}$ by the projected increase in mean temperature. K-Hidra is used as observation in
Figure 5. Binning curves of daily TP P99 vs. daily near-surface temperature averaged over 59 KMA stations during REF (green), and FUT (red), and ‘adjusted REF’ which is a version of the REF curve shifted by 7% per ◦C of projected warming between the two periods (blue). The black line is the binning curve from KMA-Sta. The shading marks one standard deviation among the 59 stations for REF, FUT, and KMA-Sta.

To examine the model’s ability to represent a realistic extreme precipitation-temperature relationship, we first focus on the REF \( A_{S99} \) for ascertaining whether the model can well describe the observed impact of daily temperature variation on extreme TP. The estimation from K-Hidra indicates an averaged \( A_{S99} \) at 7.8%/◦C across South Korea, with a higher rate in the western parts and a lower rate along the east coast (figure 4). Here, the \( ENS_{GCM-REF} \) shows a far underestimated \( A_{S99} \) rate in TP, while WRF20 and WRF05 exhibit a much higher value. In particular, for the \( A_{S99} \) in \( ENS_{WRF05-REF} \), although the rate is slightly lower than K-Hidra, it shows a similar spatial gradient and the average \( A_{S99} \) remains approximately at CC rate (6.2%/◦C). Despite having a similar spatial pattern and magnitude, \( ENS_{WRF05-REF} \) presents the noticeable low \( A_{S99} \) along the east coast, which shows the added value of the higher resolution to better elucidate the topographical effect along the high altitude region that has a lower AS rate (Shi and Durran 2016). The binning curves also reveal that the original GCMs fail to capture the observed curve shape, particularly for CCSM4\(_{GCM-REF} \) that even loses the peak shape at the high temperature (figure 5). The observed extreme precipitation-temperature binning curve in South Korea shows a peak-like structure, with the highest precipitation intensity occurring at the ‘peak temperature’ (\( T_{peak} \)) around 24 ◦C. In comparison, WRF20 does significantly improve the shape of the curves, but they underestimate the extreme precipitation, especially for those around the \( T_{peak} \). For all the models, WRF05 exhibits a clear added value by well capturing the curve shape, the \( T_{peak} \), and the extreme intensities.

To reveal the extreme precipitation-temperature relations for CP and LP respectively, figures S9–S12 are the same as figures 4 and 5, but they are calculated from the CP/LP component of the extreme events. The result shows that the difference in the \( A_{S99} \) spatial pattern of CP among the different resolutions is smaller than that for the TP (figure S9). For ENS, the simulated REF \( A_{S99} \) shows super-CC scaling in all resolutions, but the GCMs (except HadGEM2) do not capture the peak shape in the binning curve as WRF20 and WRF05 (figure S10). In WRF20, the \( A_{S99} \) magnitude is around 1–2%/◦C higher than WRF05 across the entire region, which is consistent with a larger sensitivity in CP in the 20 km grid as mentioned above. Meanwhile, the LP displays a much larger discrepancy in the \( A_{S99} \) and the binning curves among different resolutions (figures S11 and S12). The \( A_{S99} \) in \( ENS_{GCM-REF} \) is negative and the binning curves show a decreasing trend beginning from 12 ◦C to 14 ◦C. For WRF20 and WRF05, the \( A_{S99} \) in ENS is
largely positive and the rate is higher in WRF05 with an average of 5%/°C over South Korea. The AS_{99} shows a high similarity between ENS and PGW for both downsampling of WRF20 and WRF05 with regard to both CP and LP, despite the huge difference in ENS_{GCM-REF} and PGW_{GCM-REF}.

A comparison of AS_{99} rates between REF and FUT for either TP or CP/LP reveals similar patterns for both the spatial distribution as well as the magnitude for all the models, resolutions, and types of precipitation. The red binning curve of the FUT also shows a similar shape as that of the REF, but the curve is shifted upward and to the right with warming, thus indicating a higher T_{peak} and increased precipitation for the future. In general, the FUT curve is close to the blue line of ‘adjusted REF’, thereby implying that the projected future precipitation is primarily increased by the thermodynamic factor at CC rate that induces a wetter and warmer future condition. A close look at the FUT curve for CP (figure S10) shows a higher similarity with the corresponding blue line. On the other hand, a larger deviation is found for LP (figure S12), implying that other impacts such as the change of large-scale circulations on the LP.

Such shifted pattern in the binning curves of REF and FUT indicates that the future extreme precipitation cannot be simply projected by the AS rate in the current climate, established in prior studies as well (Wang et al 2017, Sun et al 2020). This is because the T_{peak} will also be changed. In this study, the CS_{99} rate, which calculates the extreme precipitation-temperature relations with the projected change between FUT and REF, demonstrates again that the scaling relations in the current climate cannot project the change in future precipitation. For both ENS and PGW, the CS_{99} shows a distinguishable difference from AS_{99} for each type of precipitation. The CS_{99} patterns reflect the spatial signature that precipitation increase is stronger in the southern part of South Korea, whereas the PGW_{WRF05} projects a slightly stronger rise than ENS_{WRF05} that reflects the significant contribution of thermodynamic factors to the increase in precipitation. Despite having a different spatial distribution from that of AS_{99}, the CS_{99} averaged over the land of South Korea is still around the CC rate (5.7%/°C in ENS_{WRF05} and 7%/°C in PGW_{WRF05}), with CP showing larger CS_{99} sensitivity than LP. Nevertheless, CP does not present the super CC scaling in CS_{99} as high as that in AS_{99}, thus indicating that its increase along the warming continues to be dominated by a thermodynamical rise in the moisture content.

The CS_{99} here is derived by scaling with the local temperature (i.e. use the temperature from the individual grid box in equation (5) following Sun et al (2020) and Wang et al (2017). However, the question that precipitation extremes in precipitation show deviation from the scaling with the local land temperature due to the advection of water vapor from elsewhere (e.g. transported by atmospheric rivers) also assumes significance. In this regard, figure S13 displays the CS_{99} rate normalized by the global mean surface temperature (GMST) (i.e. use GMST for equation (5)). Indeed, the CS_{99} due to GMST increase is much higher in this case for all types of precipitation considered, because the temperature increase in South Korea is higher than the global average. However, this CS_{99} also does not reveal any similar spatial pattern to that of AS_{99}. This again emphasizes the non-linear relationship in the local precipitation change with the temperature. Therefore, while thermodynamic law may play a key role in governing the change, it is still necessary to conduct the dynamical simulation for carefully considering all the physical processes. On the other hand, since local factors strongly affect the regional precipitation changes under global warming, especially for those relevant with dynamical factors, the exact rates of AS and CS and their relationships at different regions need to be studied on a case-by-case basis through the continuous practice of regional dynamical downsampling.

4. Discussion and conclusion

This study demonstrates the added value of the 5 km high-resolution RCM in consistently improved representation of JJA precipitation for all the downscaled models. The performance shown by ENS_{WRF05-REF} is comparable to that downscaled by the perfect boundary condition, and even to the observation, in terms of either the mean or the extreme events. The projected precipitation change from both ENS_{WRF05} and PGW_{WRF05} is in line with previous findings that there will be intensified TP, especially for the extreme, over this region. Yet as the first 5 km high-resolution downscaling product of multi-GCMs over this region, we also posit that the uncertainty and spread in the change signal may still exist over the middle of the Korean Peninsula, especially under a low warming level.

While the improved TP magnitude and spatial pattern are intuitively recognized as the added value of the increasing resolution, the reduction of the unrealistic active triggering of convection in high resolution (Jin et al 2016) is often neglected, despite the fact that our study domain—South Korea should be a moist monsoon region with prevailing LP (Sohn et al 2013, Park and Min 2017). The reduction of excessive CP in the 5 km resolution downsampling, which also alleviates the overall wet bias in TP compared to WRF20, enhances the reliability of the projected CP/LP change. The high-resolution projection of WRF05 supports that CP, whose rise has been explained by increased instability due to the increased moisture at a low level during warming (Hong and Ahn 2015), shows a higher temperature sensitivity and contributes more to the projected TP increase.
However, it also indicates that LP could also experience an increase in the future under a specific scenario/over a certain area. Importantly, the LP change is highly correlated to the dynamical change in large-scale circulation, e.g. the projected southward shift of EASM (Li et al 2010), which remains highly uncertain in either GCM or RCM simulations. For example, while CMIP5 ensemble simulations exhibit a slight negative dynamic effect on the future EASM rain band, the new CMIP6 simulations indicate a significant positive contribution from it (Wang et al 2021). According to the result from our idealized warming experiment, the LP will show an increasing trend impacted by the climatological increase of atmospheric moisture content, at a sub-CC rate that is around half of the simulated CP sensitivity. The different sensitivities of CP and LP to the temperature warming again stress the importance of realistic representation of both components for the reliable precipitation TP projection.

For further investigation of the physical realism in the simulation across different resolutions, we focus on the extreme precipitation-temperature relations in this study since its variation is more robust following the basic thermodynamic law. Although it has recently been suggested that the response of extreme precipitation to temperature changes in the current climate is not the same as the response due to climate change, we explore both to (a) seek a process-based added value of the 5 km high resolution by comparing the simulated precipitation-temperature scaling relation during REF; and (b) provide a first-time comparison of AS and CS from the perspective of high-resolution RCM simulation. On the one hand, WRF05 shows a more realistic representation of extreme TP and its scaling behavior. On the other hand, the binning curves for the FUT resemble that from shifting the REF curve toward a wetter and warmer direction with CC rate, indicating that the within-epoch scaling sensitivities will not change but will 'transfer' to the warmer world. Unsurprisingly, the between-epoch scaling sensitivity (CS) pattern for the extreme precipitation does not present correlations with AS. The shift of $T_{\text{peak}}$ on the binning curve is not linearly scaled with the warming in the mean temperature due to a general decrease of relative humidity over land as the Earth warms (Wang et al 2017), but it can also be impacted by dynamic factors other than the CC scaling. Previous studies have indicated that CS is lower than REF AS in North America (Sun et al 2020) and lower in Australia (Bao et al 2017), both of which focus only on the scaling of TP. By the 5 km high-resolution simulation, our result suggests that while the average $CS_{P99}$ of TP over South Korea's land is around CC rate, CP shows a relation of $CC < CS_{P99} < AS_{P99}$, and LP exhibits a relation of $CC > CS_{P99} > AS_{P99}$. It indicates that despite the huge difference in scaling sensitivity within the current climate, both CP and LP display a scaling relation with global warming that is generally controlled by the thermodynamical increase in the moisture content. However, the sensitivity of CP continues to be higher than that of LP in the CS, thus contributing more to the TP change, which is in line with the previous finding. This study marks the first trial of the investigation into the relationship between AS and CS in less-than-10 km, high-resolution climate simulation and for the CP/LP component. However, we narrow our focus to just one specific region and use only one RCM for downscaling. Future studies over more regions with diverging climate characteristics and using different RCMs are necessary to better understand the underlying mechanisms regarding the difference between AS and CS. Also, the first-order quantile regression is used for AS estimation in this study due to the limitation of sample sizes, which may potentially provide a lowering slope of the peak-like binning curve. For future studies, some newly-developed approaches such as piecewise regression or locally-weighted scatter plot smoothing regression (Pumo et al 2019) can be tested for obtaining more accurate AS rates.

This study explores the distinct added value of the 5 km high-resolution climate simulation from the perspective of reproduction and projection of precipitation over South Korea, particularly from the perspective of improved physical realism in the extreme precipitation—temperature sensitivities. Although it is impossible to validate the precipitation projection with observation, the high-resolution simulation with improved physical processes still sheds light on our understanding of regional climate change. However, as mentioned above, the change of EASM circulation, which can greatly affect the local precipitation over this region, remains highly ambiguous. Further work is still necessitated for in-depth thermodynamic and dynamic analyses of the projected change to reach a better understanding of the precipitation system over this region in the future. Also, it is acknowledged that RCM is under the transition to next-generation, convection-permitting RCM with the growing computation power, which potentially offers a better description of the convection activities (e.g. Pichelli et al 2020). However, it may still take several years before the extensive use of long-term convection-permitting simulations. Against this backdrop, the proven added value for 5 km dynamical downscaling in this study is not trivial for extending our understanding of the regional climate change and motivating the continuous marching into the era of high resolution RCM.

**Data availability statement**

The data that support the findings of this study are available upon reasonable request from the authors.
Acknowledgments

This study was supported by the Korea Meteorological Administration Research and Development Program under Grant KMI2021-00912. This study was also partly supported by the Special Research Support Scheme from the Hong Kong University of Science and Technology (R9055), which was funded with the donation from the Chau Hoi Shuen Foundation. The observation data K-Hidra is provided by Prof. Ahn K-H and Noh G-H. We would thank the anonymous reviewers for the constructive comments that helped to improve this paper. We would like to extend our gratitude to Prof. Kwon H-H for some valuable discussion.

ORCID iDs

Liying Qiu  @ https://orcid.org/0000-0001-9944-4311
Eun-Soon Im  @ https://orcid.org/0000-0002-8953-7538

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