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HCPD-CA High-resolution climate projection dataset in Central Asia for ecological and hydrological applications

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Abstract

Central Asia (referred to as CA) is one of the climate change Hot-Spots due to the fragile ecosystems, strained water resources, and accelerated glacier melting, which underscores the need of high-resolution climate projection datasets for application to vulnerability, impacts, and adaption assessments in ecological and hydrological systems. In this study, a high-resolution (9km) climate projection dataset over CA (the HCPD-CA dataset) is derived from dynamically downscaled results based on multiple bias-corrected global climate models, and contains ten meteorological elements that are widely used to drive ecological and hydrological models. The reference and future periods are 1986-2005 and 2031-2050, respectively. The carbon emission scenario is Representative Concentration Pathway (RCP) 4.5. The results show the data product has good quality in describing the climatology of all the elements in CA, which ensures the suitability of the dataset for future research. The main feature of projected climate changes in CA in the near-term future is strong warming (annual mean temperature increasing by 1.62-2.02°C) and significant increase in downward shortwave and longwave flux at surface, with minor changes in other elements (e. g., precipitation, relative humidity at 2m, and wind speed at 10m). The HCPD-CA dataset presented here serves as a scientific basis for assessing the impacts of climate change over CA on many sectors, especially on ecological and hydrological systems. It is publicly available at http://data.tpdc.ac.cn/en/disallow/24c7467c-44a6-44ab-bbcf-e6e346dd41d0/ (Qiu, 2021).

1. Introduction

Central Asia (referred to as CA, Fig. 1a) has complex terrain and diverse climates and is among the most vulnerable regions to climate change due to fragile ecosystems (Zhang et al., 2016;Seddon et al., 2016;Gessner et al., 2013), strained water resources (Frenken, 2013), and accelerated glacier melting (Narama et al., 2010;Sorg et al., 2012), which underscores the need to achieve high-resolution climate projection datasets for application to vulnerability, impacts, and adaption assessments in ecological and hydrological systems. Global

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climate models (GCMs) can describe the response of the global circulation to large-scale forcing, such as greenhouse gases and solar radiation (Giorgi, 2019). But their horizontal resolutions are too coarse to account for the effects of local-scale forcing and processes, such as complex topography, land cover distribution, and dynamical processes occurring at the mesoscale (Giorgi et al., 2016;Qiu et al., 2017;Torma et al., 2015). Regional climate models (RCMs) have been applied to downscale the GCM outputs to finer scales in CA (Zhu et al., 2020;Ozturk et al., 2017;Mannig et al., 2013). However, their resolutions are still low (≥30km), especially for the mountainous areas in the southeast. Moreover, most of the previous RCM simulations used a single GCM as the lateral boundary conditions, which harbor high uncertainties in the projected climate changes.

The present authors carried out a study that involves the dynamical downscaling of multiple bias-corrected GCMs for the CA region with an unprecedented horizontal resolution of 9km. The future simulation period is set as 2031-2050 under Representative Concentration Pathway (RCP) 4.5, with the reference period of 1986-2005. The simulated surface air temperature and precipitation have been evaluated in a recent study (Qiu et al., 2021) and meanwhile basic features of the projected climate changes have been demonstrated. The results show that the high-resolution RCMs driven by bias-corrected GCMs are excellent in simulating the local temperature and precipitation in CA and detect significant warming, severer heatwaves, and drier conditions in this region in the near-term future.

To satisfy the urgent need of high-resolution climate data for ecological and hydrological applications in CA, the HCPD-CA (High-resolution Climate Projection Dataset in CA) dataset is derived from the 9-km resolution downscaled results, which includes ten meteorological elements (Table 1) that are widely used to drive ecological and hydrological models. They are daily precipitation (PREC, mm/day), daily mean/maximum/minimum temperature at 2m (T2MEAN/T2MAX/T2MIN, K), daily mean relative humidity at 2m (RH2MEAN, %), daily mean eastward and northward wind at 10m (U10MEAN/V10MEAN, m/s), daily mean downward shortwave/longwave flux at surface (SWD/LWD, W/m^2), and daily mean surface pressure (PSFC, Pa). The present paper is to introduce this dataset to the community. Sect. 2 describes the regional model and experiments. Model evaluation and projected changes in these elements are in Sect. 3. Added values of using 9-km resolution respect to using coarser resolutions are discussed in Sect. 4 as well as uncertainties of the dataset. Sect. 5 describes access to the data product and all codes and tools. Main results are concluded in Sect. 6.

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2 Model and experiments

2.1 Regional model

The Weather Research and Forecasting (WRF) model with version 3.8.1 (Skamarock et al., 2008) is used to downscale the GCMs. It has two domains (Fig. 1b). The outer one covers a large region, with a 27-km resolution and 290×205 grids. The inner one covers the CA region, with a 9-km resolution and 409×295 grids. The model has 33 levels in the vertical direction with its top fixed at 50 hPa. Its physical schemes are set based on our previous work about the sensitivity study of different physical parameterizations of the WRF model in simulating the local climate in CA (Wang et al., 2020). Details about them are in Qiu et al. (2021). Spectral nudging with a weak coefficient of 3×10^{-5} is applied in the outer domain (not in the inner one), which prevents possible model drift during the long-term integration by relaxing the model simulations of wind, temperature, and moisture toward the driving conditions. In addition to greenhouse gases and solar constant, the WRF model also considers other external forcing, such as aerosols, volcanoes, and ozone, to make its inner external forcing consistent with the driving GCMs.

2.2 Bias-correction technique

MPI-ESM-MR (referred to as MPI, Table 2), CCSM4 (referred to as CCSM), and HadGEM2-ES (referred to as Had) from Phase 5 of the Coupled Model Intercomparison Project (CMIP5) are selected to drive the regional model. Since all GCMs suffer from some forms of bias (Done et al., 2015;Ehret et al., 2012;Liang et al., 2008;Xu and Yang, 2012) that may propagate down to the RCM outputs, the bias-correction technique developed by Bruyère et al. (2014) is applied in this study to correct the climatology of the GCMs and allow synoptic and climate variability to change.

Six-hourly GCM data in a 25-year base/future period (1981-2005/2026-2050), hereafter referred to as GCM_{BP}/GCM_{FP}, are broken down into the 25-year mean 6-hourly annual cycle over the base period ($\overline{GCM_{BP}}$) plus a 6-hourly perturbation term (GCM_{BP}'/GCM_{FP}'):

$$GCM_{BP} = \overline{GCM_{BP}} + GCM_{BP}' \quad (1)$$

$$GCM_{FP} = \overline{GCM_{BP}} + GCM_{FP}' \quad (2)$$

The ERA-Interim reanalysis data (Dee et al., 2011, Table 2) as “observations” (Obs) is similarly broken down into the mean annual cycle ($\overline{Obs}$) and a perturbation term (Obs'):

$$Obs = \overline{Obs} + Obs' \quad (3)$$

The bias corrected GCM data for the base/future period, $GCM_{BP}{}^{*}/GCM_{FP}{}^{*}$, is then constructed by replacing $\overline{GCM_{BP}}$ from Eq. 1/2 with $\overline{Obs}$ from Eq. 3:

$$GCM_{BP}{}^{*} = \overline{Obs} + GCM_{BP}{}' \quad (4)$$

$$GCM_{FP}{}^{*} = \overline{Obs} + GCM_{FP}{}' \quad (5)$$

Eq. 1-5 are applied to all the variables required to generate the initial and lateral boundary conditions for the WRF model: zonal and meridional wind, geopotential height, air temperature, relative humidity, sea surface temperature, mean sea level pressure, etc.

2.3 Experiments

The RCM simulations with the bias-corrected GCMs (MPI, CCSM, and Had) as the driving data are referred to as WRF_MPI_COR, WRF_CCSM_COR, and WRF_Had_COR, respectively ("COR" means using the bias-correction technique). The reference-period simulations are from December 1, 1985 to December 31, 2005 and the future runs are from December 1， 2030 to the end of 2050 under a moderate carbon emission scenario RCP 4.5, which is arguably the most policy-relevant scenario as the Nationally Determined Contributions (NDCs) greenhouse gas emissions framework would produce similar temperatures trajectories (Gabriel and Kimon, 2015). The first month in each simulation is discarded as spin up. Fig. 2 shows the flow chart to produce the HCPD-CA dataset.

3 Results

3.1 Model evaluation

In Qiu et al. (2021), the key meteorological elements, surface air temperature and precipitation, have been evaluated with both gridded observations and stations' data (see Sect. 3.1 in the paper) and the results show good skills of the regional model in simulating the local temperature and precipitation in CA during the reference period (1986-2005). Accordingly, the ten meteorological elements (including surface air temperature and precipitation) in the HCPD-CA dataset are evaluated here, to show the validity and applicability of the dataset. Note that daily mean wind speed at 10m (referred to as WS10MEAN) instead of U10MEAN and V10MEAN is evaluated.

Version 4 of the Climatic Research Units gridded Times Series (CRU TS v4, Harris et al., 2020, Table 2) is applied to evaluate T2MEAN/T2MAX/T2MIN and the fifth generation ECMWF (European Center for Medium Weather Forecasting) atmospheric reanalysis (ERA5, Hersbach et al., 2020, Table 2) land monthly averaged data (referred to as ERA-Land) is used as observations to evaluate other elements. Before the evaluation, the RCM outputs are interpolated to the grides of CRU TS v4 (ERA5-Land) with the distance-

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weighted average (bilinear) method. We found that both on the annual and seasonal scales, the interpolation methods conserved the area averaged values in the model outputs with a bias of less than 1-2% between the original and new grids. We thus concluded that our choice of interpolation procedure does not affect the main conclusions of our work.

The high-resolution downscaled results (WRF_MPI_COR, WRF_CCSM_COR, and WRF_Had_COR) are very close to the observational data in simulating the climatology of all the elements in CA on the annual and seasonal scale (Fig. 3-5, seasonal results not shown here). For instance, the spatial correlation coefficients (SCCs) of all the elements except WS10MEAN are larger than 0.80. The SCCs of WS10MEAN are relatively small, in a range of 0.54-0.60. The regional model overestimated SWD, with the mean errors (MEs) in a range of 26.61-29.77 W/m^2. Fig. 6 shows mean annual cycle of the monthly values averaged over CA. It is seen that the model outputs are generally close to the observations. The overestimation of SWD occurs throughout the year, with the bias larger in the warm seasons than in the cold seasons (Fig. 6e). The results of T2MAX and T2MIN are similar to those of T2MEAN (not shown here).

To sum up, the model evaluation shows the HCPD-CA dataset has good quality in describing the climatology of all the ten meteorological elements in CA, which ensures the suitability of the dataset for ecological and hydrological applications.

3.2 Projected climate changes

Fig. 7 shows projected changes of the annual mean values in CA during 2031-2050, relative to 1986-2005. All the RCM simulations exhibit significant warming over CA in the near-term future, with the annual mean T2MEAN increasing by 1.62-2.02℃ (Fig. 7a-c). Pronounced warming is found in the north, which is attributed to the snow and surface albedo feedback (Qiu et al., 2021). Interestingly, enhanced warming projected in many mountains in the world (Palazzi et al., 2019;Pepin et al., 2015;Rangwala et al., 2013) is not found in CA (see Fig. 8 in Qiu et al. (2021)). It poses a question if the responses of ecological and hydrological systems to future warming in the Tien Shan and Pamirs differ from those in other mountains, like Tibetan Plateau/Himalayas and Alps.

The annual mean precipitation (PREC) is projected to sightly increase by 0.01-0.02 mm/day (Fig. 7d-f). However, changes in few areas passed the significance test. The annual mean RH2MEAN is projected to sightly decrease by 0.68-1.28% (Fig. 7g-i), which suggests a drier condition in CA in the coming decades and may affect the physical and chemical properties of the local vegetations. Changes in wind speed (WS10MEAN) are inconsistent among the RCM simulations (Fig. 7j-l). WRF_MPI_COR shows a slight increase of 0.02m/s while others show a slight decrease. Downward shortwave/longwave flux (SWD/LWD) are projected to

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significantly increase by 3.47-4.28 W/m^2 and 7.13-9.61 W/m^2, respectively (Fig. 7m-r). Surface pressure (PSFC) is simulated to slightly increase by 0.15-0.70 hPa in CA (Fig. 7s-u).

To sum up, the main feature of projected climate changes in CA in the near-term future is strong warming and significant increases in downward shortwave and longwave flux, with minor changes in other elements. Therefore, the HCPD-CA dataset provides extraordinary warming scenarios for assessing the impacts of future warming on the local ecological and hydrological systems in CA. Details about changes in these meteorological elements (e.g., changes at the seasonal scale) are out of the scope of the present paper and will be presented in further studies. Systematic analyses of changes in surface air temperature, heatwaves and droughts are in Qiu et al. (2021).

4 Discussion

4.1 9km vs 27km

As discussed above, most of the previous RCM simulations in CA have horizontal resolutions not higher than 30km. To show the added values of using 9-km resolution in this study respect to using coarser resolutions, the evaluation metrics (SCC and RMSE) of the simulated 9-km resolution precipitation in the inner domain of the WRF model are compared with those of 27-km resolution precipitation in the outer domain (Fig. 8). As the gridded observations (CRU TS v4, and ERA5-Land) have potential limitations in depicting the climatology of the elements in CA, the metrics are calculated based on 58 stations' data across CA (see red dots in Fig. 1a) which have been quality controlled (Qiu et al., 2021). Note that a station is compared with the model grid on which it is located.

Compared with the 27-km resolution data, the 9-km resolution data largely increases SCCs and reduces RMSEs, especially over the mountainous areas (see the subregion "MT" in Fig. 1c). For instance, over the mountainous areas, the ensemble-mean SCC of annual precipitation increases from 0.38 to 0.58 (Fig. 8c) and the ensemble-mean RMSE of annual precipitation decreases from 1.30 to 1.14 mm/day (Fig. 8d). This highlights the necessity of improving the model resolution from ≥30km to 9km and the advantages of using the HCPD-CA dataset for researches in CA.

4.2 Uncertainties

With the limitation of the computational and time cost, this study used three bias-corrected GCMs from CMIP5 to do the dynamical downscaling over CA, which is an improvement relative to using a single original GCM. However, it still harbors uncertainties in the projected climate changes. As reported in the 1.5°C special

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report of the Intergovernmental Panel on Climate Chane (IPCC), we are on track to exceed 1.5℃ warming between 2030 and 2052 based on the current warming rate, and hence the near-term future projection becomes more critical to human development than that for the end of this century. Therefore, this study focuses on climate changes over CA in the near-term future (2031-2050). Long-term continuous (e.g., 1986-2100) regional climate projections in CA are more useful for studies in this region and will be conducted in the next stage. Land-use and land-cover (LULC) in the WRF model is derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) data of 2002 (Wang et al., 2007). Dramatic changes in water extent of the Aral Sea (Micklin, 2007) are not taken into account during the simulations, which brings uncertainties in simulating the local climate in this area as well as projecting the climate changes caused by changes in LULC.

5. Data and code availability

The HCPD-CA dataset is available at http://data.tpdc.ac.cn/en/disallow/24c7467c-44a6-44ab-bbcf-e6e346dd41d0/ (Qiu, 2021). The files are stored in netCDF4 format and compiled using the Climate and Forecast (CF) conventions. It contains ten meteorological elements from three RCM simulations (WRF_CCSM_COR, WRF_MPI_COR, and WRF_Had_COR) for a spatial domain covering the CA region (which is consisted of Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan) and its surrounding areas (see “D02” in Fig. 1b). The dataset covers two continuous 20-year periods, 1986-2005 and 2031-2050. Each year has 365 days (there is no leap year). We provide smaller-size (monthly and annual) files as surrogates for larger-size (daily) files. The names of the files follow the order: [dataset name]_[experiment name]_[element name]_[year].[time frequency].nc. For example, the file name, HCPD-CA_WRF_CCSM_COR_T2MAX_2004.mon.nc, represents the monthly mean T2MAX of 2004 from the experiment WRF_CCSM_COR in the HCPD-CA dataset.

The WRF model is available at https://www2.mmm.ucar.edu/wrf/users/download/get_source.html. The source code to do the bias correction is available at https://rda.ucar.edu/datasets/ds316.1/#!software. The Climate Data Operators (CDO, https://code.mpimet.mpg.de/projects/cdo), Python modules (like netCDF4, Xarray, and Numpy), and NCAR Command Languages (NCL, https://www.ncl.ucar.edu/) are recommended to do operations on the netCDF files.

6. Conclusions

A high-resolution (9km) projection climate dataset in CA (the HCPD-CA dataset), containing ten meteorological elements, is derived from dynamically downscaled results based on three bias-corrected GCMs (MPI-ESM-MR, CCSM4, and HadGEM2-ES) from CMIP5 for ecological and hydrological applications in this region. The reference and future periods are 1986-2005 and 2031-2050, respectively. The carbon emission scenario is RCP4.5. The model estimation shows good quality of the data product in describing the climatology of all the elements in CA, which ensures the suitability of the dataset. The RCM simulations commonly suggest strong warming over CA in the near-term future, with the annual mean T2MEAN increasing by 1.62-2.02℃, and significant increase in downward shortwave and longwave flux. Changes in other elements (e. g., precipitation, relative humidity at 2m, and wind speed at 10m) are minor. The HCPD-CA dataset presented here serves as a scientific basis for assessing the impacts of climate change over CA on many sectors, especially on ecological and hydrological systems.

Author contribution

All the authors made contributions to the conception or design of the work. YQ did the analyses and drafted the work and others revised it.

Competing interests

The authors declare that they have no conflict of interest

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Tables and Figures

Table 1 Meteorological elements in the HCPD-CA dataset

Element name	**Description**	**Unit**
PREC	Daily precipitation	mm/day
T2MEAN	Daily mean temperature at 2m	K
T2MAX	Daily maximum temperature at 2m	K
T2MIN	Daily minimum temperature at 2m	K
RH2MEAN	Daily mean relative humidity at 2m	%
U10MEAN	Daily mean eastward wind at 10m	m/s
V10MEAN	Daily mean northward wind at 10m	m/s
SWD	Daily mean downward shortwave flux at surface	W/m^2
LWD	Daily mean downward longwave flux at surface	W/m^2
PSFC	Daily mean surface pressure	Pa

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335 **Table 2** Information about the datasets used in the study.

Dataset	Run	Spatial Resolution	Temporal Resolution	Link
MPI-ESM-MR	r1i1p1	1.9°×1.9°	6-hourly	https://esgf-node.llnl.gov/projects/cmip5/
HadGEM2-ES	r1i1p1	1.3°×1.9°	6-hourly	https://esgf-node.llnl.gov/projects/cmip5/
CCSM4	b40.[20th\RCP 4.5].track1.1deg.012.cam2.h4	0.9°×1.3°	6-hourly	https://rda.ucar.edu/datasets/ds316.0/#!access
ERA-Interim	-	0.75°×0.75°	Synoptic monthly means	https://apps.ecmwf.int/datasets/data/interim-full-mnth/levtype=sfc/
CRU TS v4	-	0.5°×0.5°	monthly	https://crudata.uea.ac.uk/cru/data/hrg/cru_ts_4.00/
ERA5-Land	-	0.1°×0.1°	monthly	https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-land-monthly-means?tab=form

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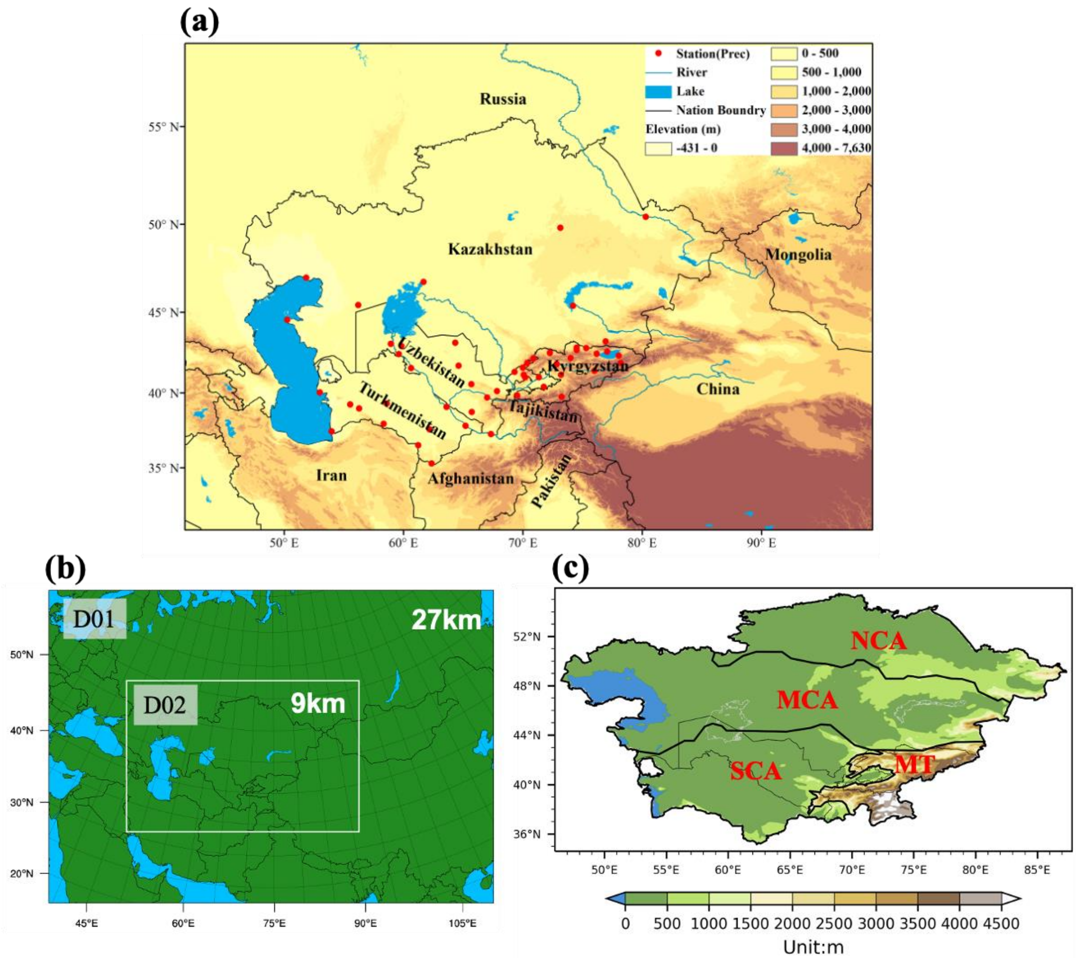

Fig. 1 Central Asia (referred to as CA) and its surrounding (a), nested domains in the WRF model (b), and climate subregions in CA (c). In subplot a, stations with records of precipitation are marked by red dots. In subplot c, according to Qiu et al. (2021), the CA region is divided into four climate sub-regions: northern CA (NCA), middle CA (MCA), southern CA (SCA), and the mountainous areas (MT). This figure is adapted from Qiu et al. (2021) and the reproduction right has been granted.

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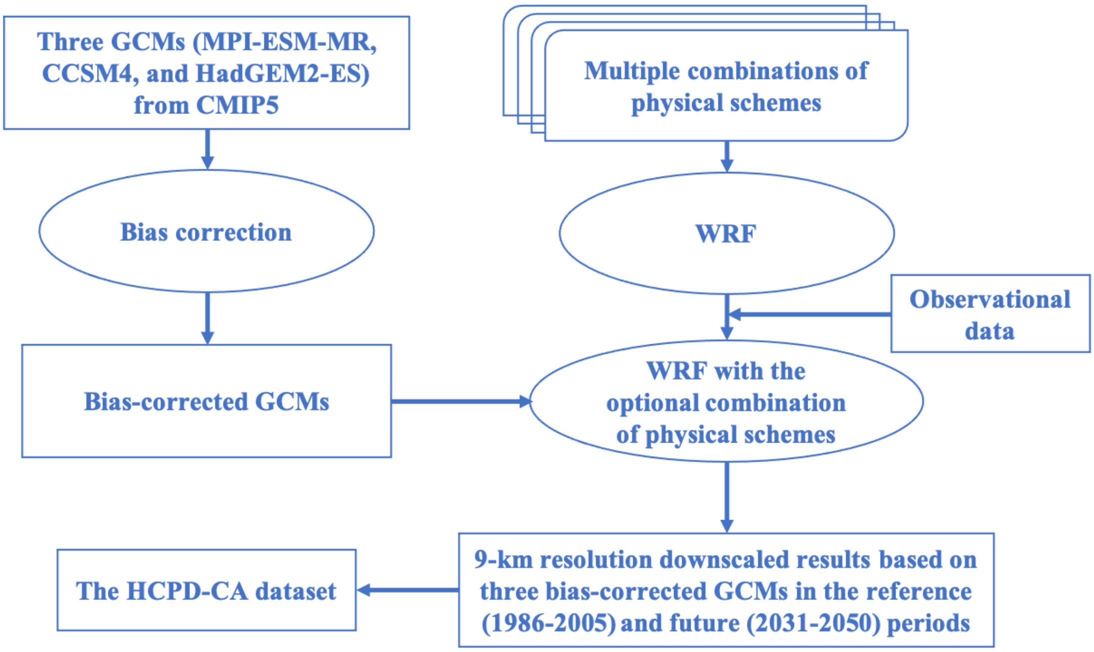

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347 **Fig. 2** Flow chart for the HCPD-CA dataset.

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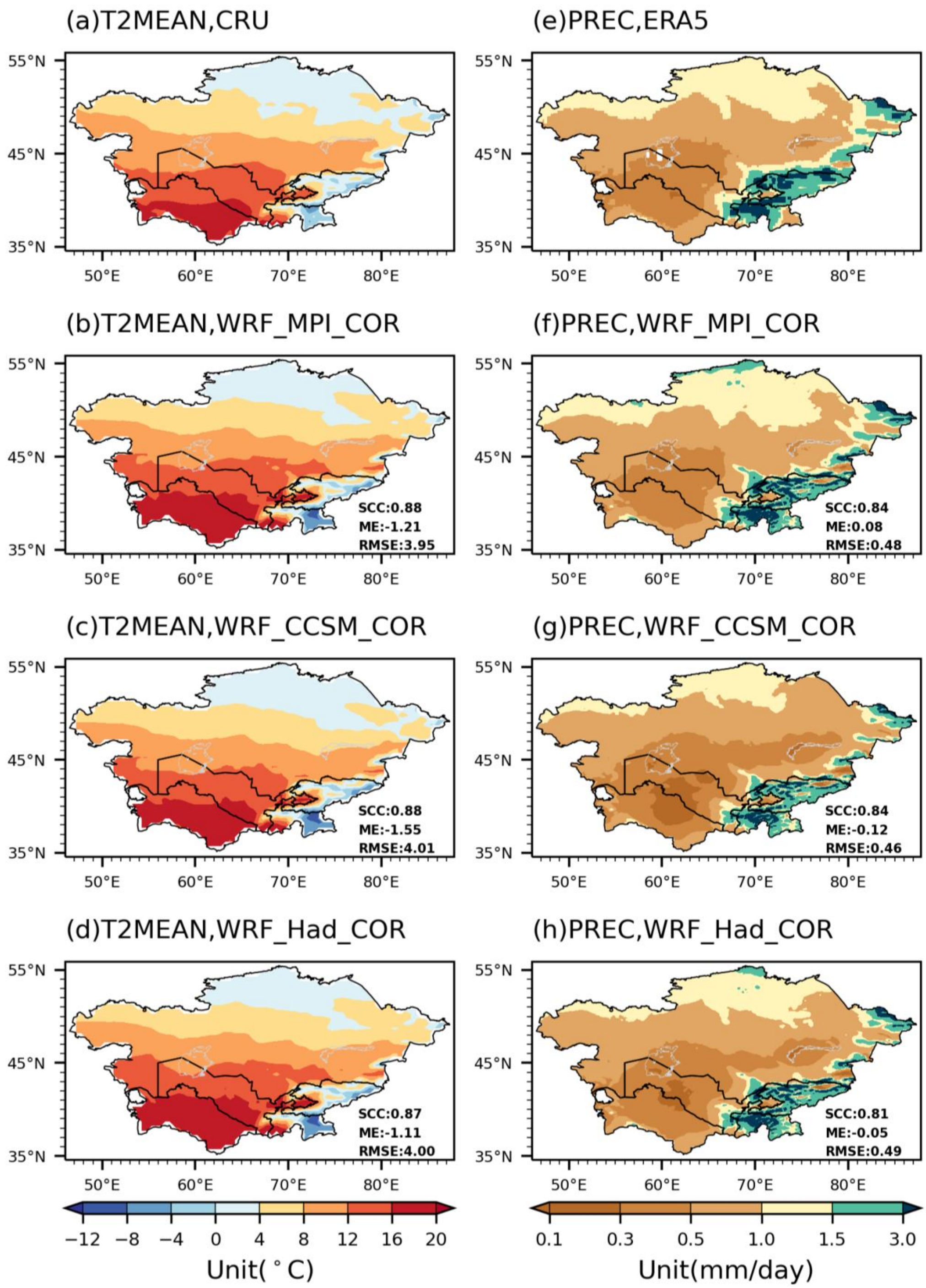

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349 **Fig. 3** The observed and simulated annual mean T2MEAN and PREC in Central Asia during the reference
350 period (1986-2005). The spatial correlation coefficient (SCC), mean error (ME), and root mean square error
351 (RMSE) are listed.

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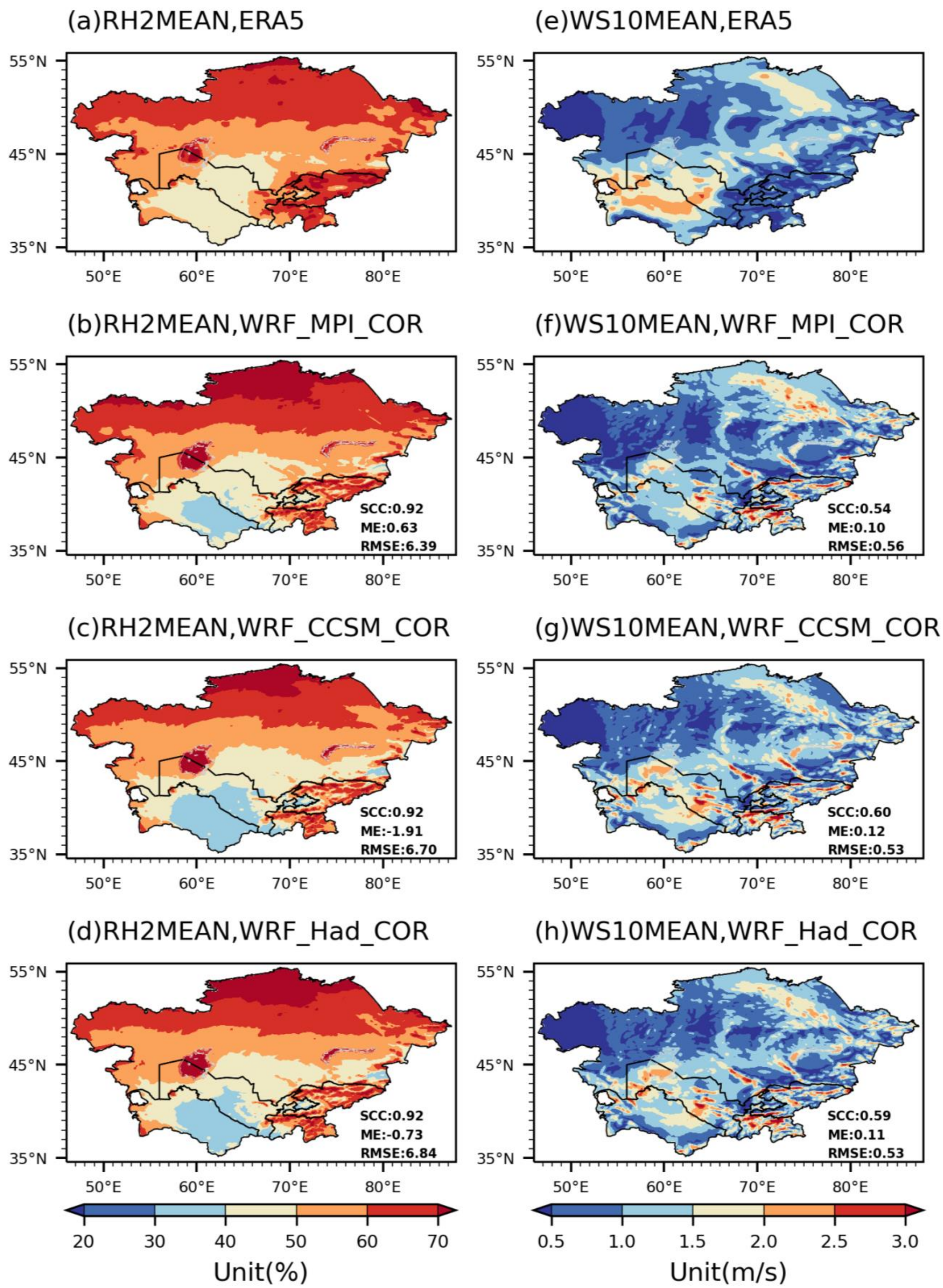

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353 **Fig. 4** Same as **Fig. 3**, but for annual mean RH2MEAN and WS10MEAN.

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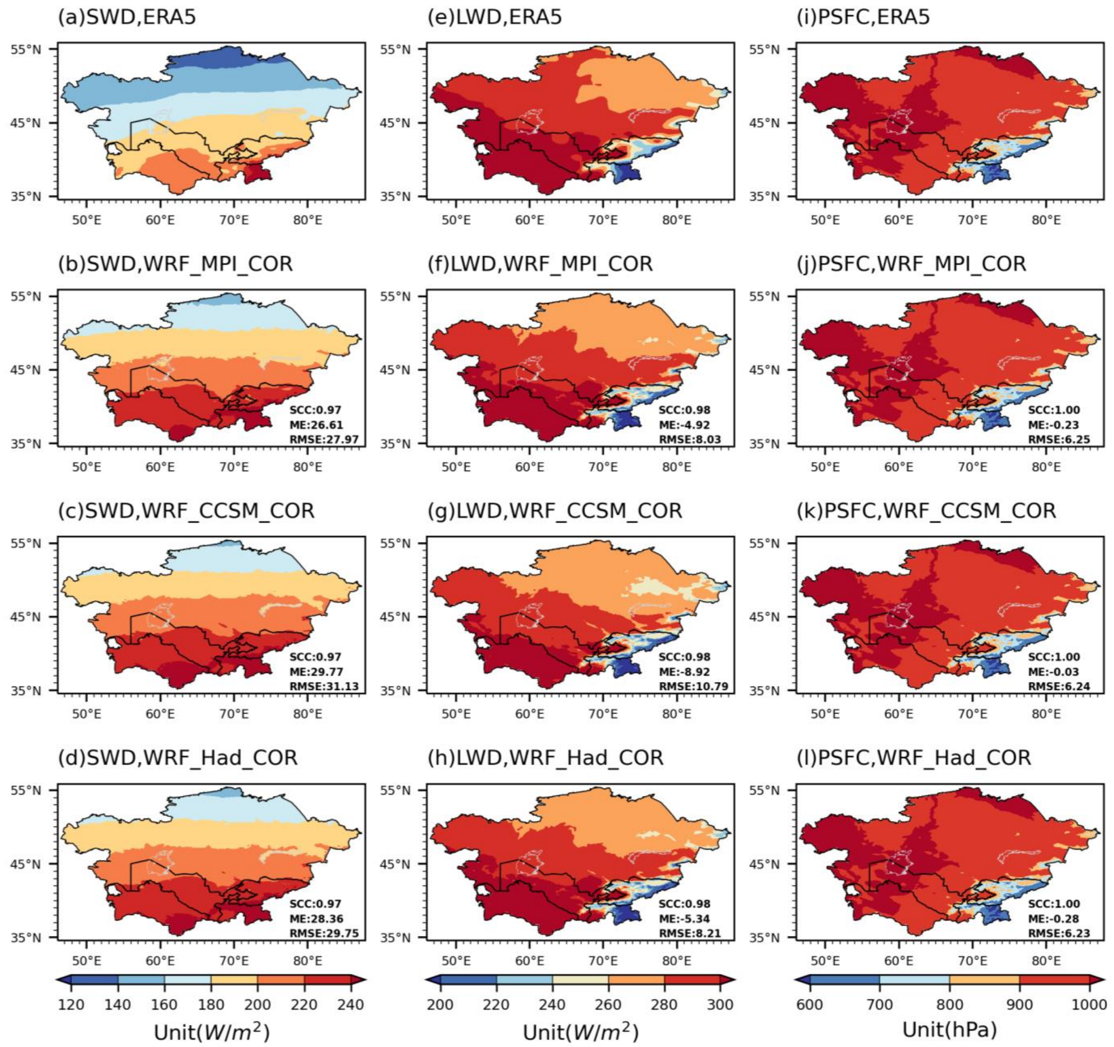

Fig. 5 Same as **Fig. 3**, but for annual mean SWD, LWD, and PSFC.

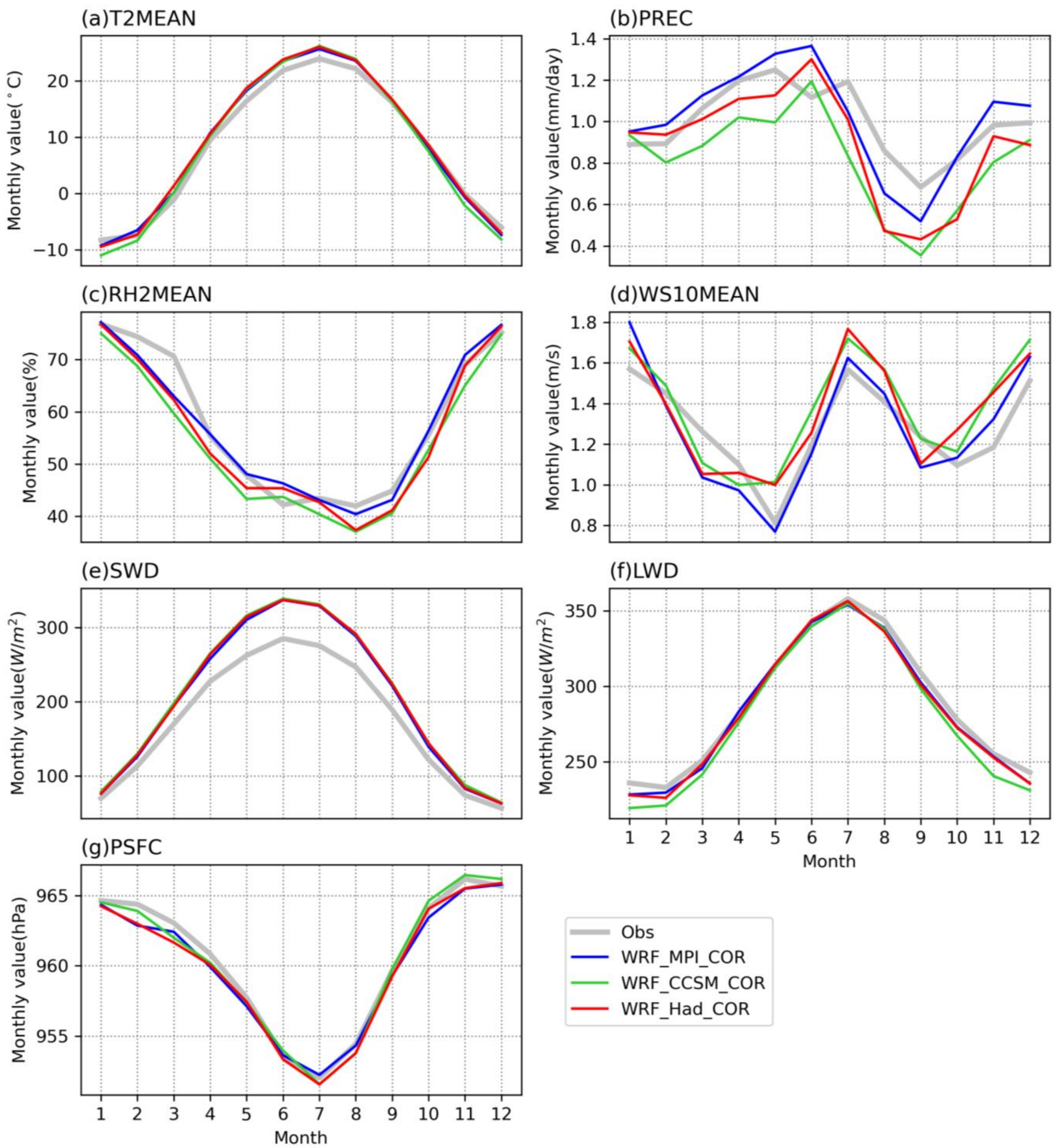

Fig. 6 Mean annual cycle of the monthly values averaged over Central Asia in the observation and RCM simulations.

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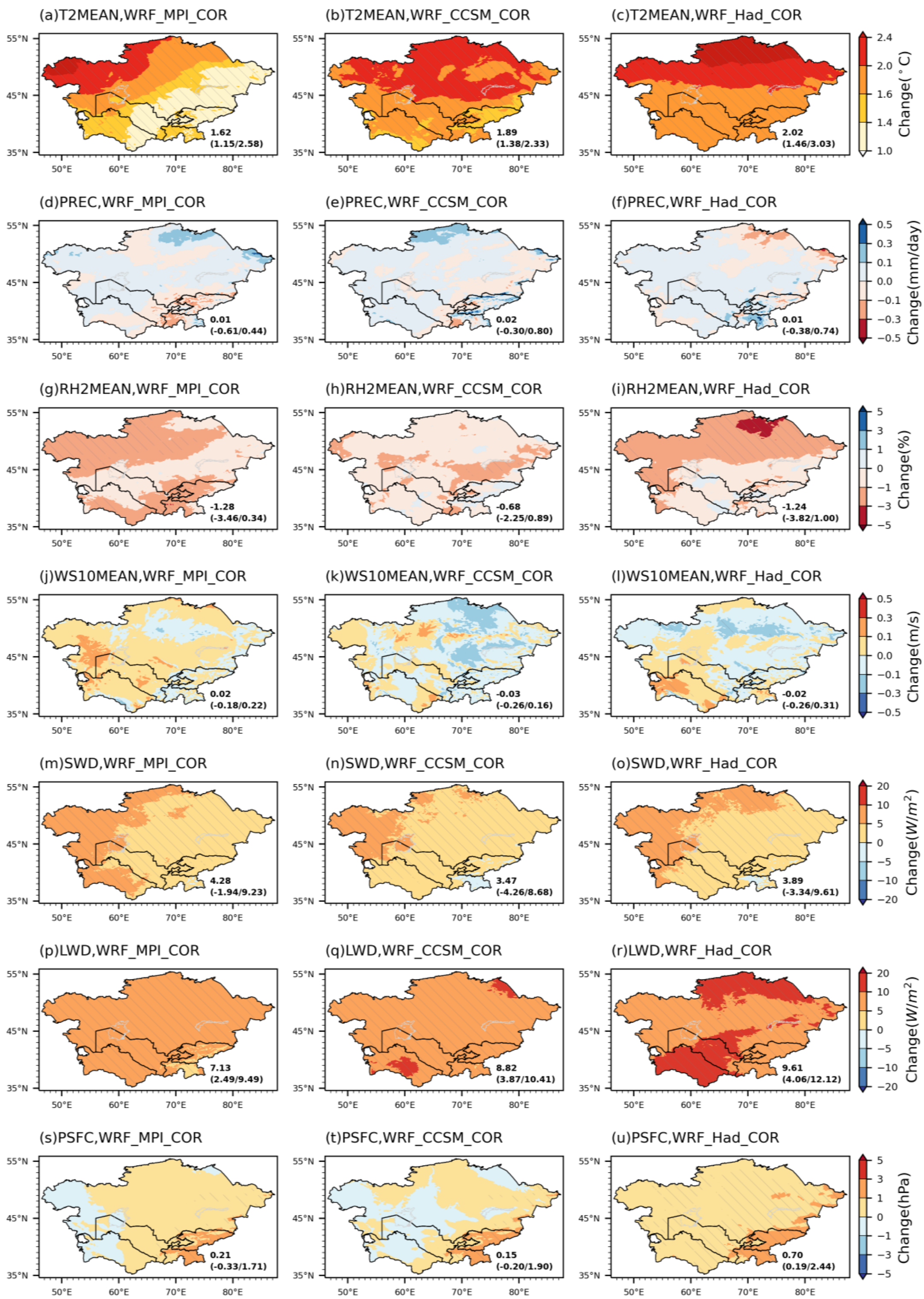

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362 **Fig. 7** Projected changes of the annual mean values over Central Asia during 2031-2050, relative to 1986-

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2005. The regional mean (upper), minimum and maximum value (in parentheses) are listed. The slashed areas indicate where the changes passed the significance test at the 95% confidence level using the two-tailed Student's t test.

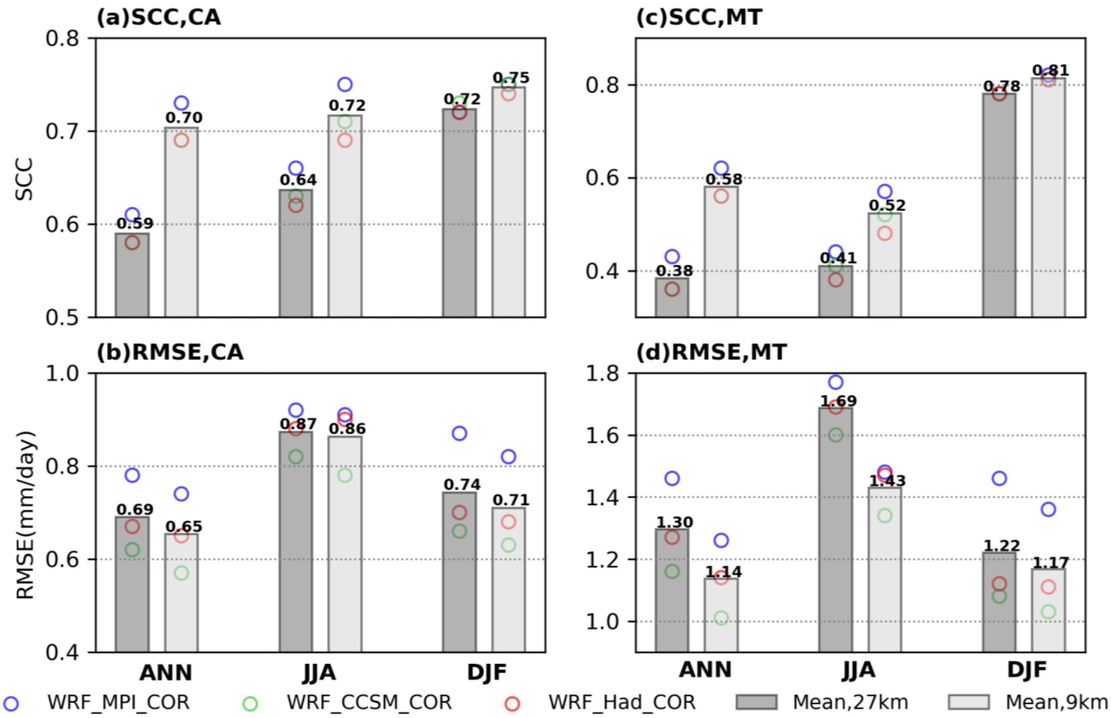

Fig. 8 Spatial correlation coefficients (SCCs) and root mean square errors (RMSEs) of the simulated annual (ANN), summer (JJA: June-July-August), and winter (DJF: December-January-February) mean precipitation over CA and the mountainous areas (MT) in the 9-km and 27-km resolution downscaled results. The metrics are calculated based on 58 stations' data across CA.